Apply Data Science for Rapid Modeling of Dual Fuel Technology for Life Cycle Assessment

Revised to include Dual Fuel Diesel Savings Information, June 28, 2018.
Please see accompanying proposal materials for details.

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The Woodlands, Texas
www.harcresearch.org
Dual Fuel Diesel Engines

Fracturing
Variable Load
Speed 1500 to 1950 rpm

Drilling
Transient Load Response
Speed 1200 rpm
Dual Fuel Diesel Engine
Diesel Fuel and Natural Gas Used Together

Fumigation Systems
Natural Gas Fuel Introduced Into Engine Air Intake in Vapor Phase

Replace Diesel Fuel with Gas Fuel

MAX SUBSTITUTION “SWEET SPOT”

Dual Fuel Diesel Displacement

Substitution / Diesel Displacement
Maximum Substitution Occurs in the Operating Range known as the “Sweet Spot”

GRAPHICS ADAPTED FROM CUMMINS
## Dual Fuel Diesel Savings

**Example – 50% Substitution of Diesel Fuel with Natural Gas**

### Table 1. Example of Dual Fuel Diesel Cost Savings

A rig that consumes 1,500 gallons of diesel fuel per day could save $888,045 annually, $2,433 daily, by substituting natural gas for 50% of the diesel fuel typically used.

**Diesel Fuel $3.24 / gallon**

EIA Diesel Fuel Price Index, June 23, 2018

[https://www.eia.gov/petroleum/gasdiesel/](https://www.eia.gov/petroleum/gasdiesel/)

<table>
<thead>
<tr>
<th>Gallons</th>
<th>Diesel Cost</th>
<th>Annual Cost</th>
<th>Gallons</th>
<th>Diesel Cost</th>
<th>Annual Cost</th>
<th>Annual Savings</th>
<th>Daily Savings</th>
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<td>$592,030</td>
<td>$592,030</td>
<td>$1,622</td>
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<td>$1,302,466</td>
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<td>$769,639</td>
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<tr>
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<td>$4,542</td>
<td>$1,657,684</td>
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<td>$828,842</td>
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<td>$888,045</td>
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<td>$2,012,902</td>
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<td>$3,244</td>
<td>$1,184,060</td>
<td>$1,184,060</td>
<td>$3,244</td>
</tr>
</tbody>
</table>

Rig using 1,500 gallons of Diesel Fuel per day

- Daily Diesel Fuel Cost Savings: $2,433
- Annual Diesel Fuel Cost Savings: $888,045

Rig using 2,000 gallons of Diesel Fuel per day

- Daily Diesel Fuel Cost Savings: $3,244
- Annual Diesel Fuel Cost Savings: $1,184,060

Please see accompanying Proposal materials for details.
Joint Industry Project
Predictive Model for Dual Fuel Operations

- **Sponsors**
  Seeking up to 12

- **Project Cost**
  Total $185,000
  Divided Among Sponsors

- **Duration**
  6-8 months

Please see accompanying Proposal materials for details.
### Table 2. Example of Dual Fuel Diesel Cost Savings with Increased Substitution

A rig that consumes 1,500 gallons of diesel fuel per day could realize an incremental savings of $177,609 annually by increasing substitution natural gas from 50% to 60%.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>1,000</td>
<td>$ 3,244</td>
<td>$ 1,184,060</td>
<td>500</td>
<td>$ 1,622</td>
<td>$ 592,030</td>
<td>400</td>
<td>$ 1,298</td>
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<tr>
<td>1,100</td>
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<td>$ 1,817</td>
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<td>$ 805,161</td>
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<td>$ 1,184,060</td>
<td>800</td>
<td>$ 2,595</td>
<td>$ 947,248</td>
</tr>
</tbody>
</table>

Rig using 2,000 gallons of Diesel Fuel per day
- **Daily Incremental Diesel Fuel Cost Savings**: $616
- **Annual Incremental Diesel Fuel Cost Savings**: $236,812

Rig using 1,500 gallons of Diesel Fuel per day
- **Daily Incremental Diesel Fuel Cost Savings**: $487
- **Annual Incremental Diesel Fuel Cost Savings**: $177,609

Please see accompanying Proposal materials for details.
Value Proposition
Increasing Diesel Fuel Savings

Project Deliverable:
Predictive Model for Dual Fuel Operations
- Diesel Fuel Consumption
- Gas Substitution
- Engine Emissions

Optimize parameters to increase gas substitution for greater diesel fuel cost savings

Confidently address environmental issues of engine emissions

ROI & Payback Period

*NOTE: The ROI and Payback Days calculated here consider only diesel fuel cost savings. This does not include the cost of natural gas fuel, which can vary considerably based upon supply availability, infrastructure, royalties, and other factors. Furthermore, these calculations do not account for the capital cost for dual fuel equipment. When these factors are considered, actual ROI would be reduced, and the number of Payback Days would increase.
Life Cycle Inventory (LCI)

- Emissions
- Fuel Supply & Consumption
  Diesel Fuel, Natural Gas Fuel
- Operational Parameters
  Anticipated Engine Loads
- Locational Factors
- Uncertainty
Predictive Model

- Dual Fuel Technology
  - Predict Fuel Costs & Emissions
  - Key Data for Life Cycle Assessment
- Data Flow In
  - Open Sources, Industry Partners
- Data Flow Out
  - Prediction: Broaden Scenarios
Data Cleaning

- Determine Applicable Features
- Purge “Bad” Data
- Harmonize definitions and methods
- Format data, ready-for-modeling
Data Analysis

• Preliminary data exploration

• Machine learning tool box
  – regression, classification

• Build model to predict
  – Fuel savings, operations and emissions
  – Key data for life cycle assessment
Data Visualization

• Predicted data and accuracy
• Correlation matrix, histogram, boxplot
• No raw (site-specific) data shared
Deliverables

• **Predictive Model Output**
  – Visualized Data and Predictions
  – Diesel & Natural Gas Fuel Consumption & Substitution Ratio
  – Engine Emissions

• **Life Cycle Assessment** (if necessary)

• **Interactive Online User Interface**
Data Exploration

Features (Steady State)

- Activity: hydraulic fracturing (HF) or drilling (DR)
- Engine make and model
- After-treatment system (ATS): e.g. DOC, SCR
- RPM, power, NG heating value, loading
- Fuel consumption (diesel, NG)
- Fuel efficiency, displaced diesel, substitution ratio
- Emissions (GHG, NMHC+NOx, CO and methane)
## Feature List Example

<table>
<thead>
<tr>
<th>Feature</th>
<th>Unit</th>
<th>Data Type</th>
<th>Calculation and method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>N/A</td>
<td>String</td>
<td>Origin of data</td>
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<tr>
<td>AverageYN</td>
<td>N/A</td>
<td>Category</td>
<td>Y-this is the average of several observations; N-this is a single and independent observation</td>
</tr>
<tr>
<td>Activity</td>
<td>N/A</td>
<td>Category</td>
<td>HF-hydraulic fracturing; DR-drilling</td>
</tr>
<tr>
<td>Engine_make</td>
<td>N/A</td>
<td>String</td>
<td>The manufacturer of the engine</td>
</tr>
<tr>
<td>Engine_model</td>
<td>N/A</td>
<td>String</td>
<td>The model of the engine</td>
</tr>
<tr>
<td>Rated_speed_rpm</td>
<td>RPM</td>
<td>Numeric</td>
<td>The rated speed of the engine</td>
</tr>
<tr>
<td>Rated_power_kw</td>
<td>kW</td>
<td>Numeric</td>
<td>Power output at 100% loading</td>
</tr>
<tr>
<td>Power_kw</td>
<td>kW</td>
<td>Numeric</td>
<td>Actual power output during operation</td>
</tr>
<tr>
<td>NG_LHV_btu/cf</td>
<td>Btu/cf</td>
<td>Numeric</td>
<td>lower heating value of NG used</td>
</tr>
<tr>
<td>Fuel_consump_DLEperkwh</td>
<td>DLE/kWh</td>
<td>Numeric</td>
<td>Total fuel consumption in diesel liter equivalent (DLE) – convert to diesel gallon equivalent (DGE)</td>
</tr>
<tr>
<td>Diesel_consump_DLEperkwh</td>
<td>DLE/kWh</td>
<td>Numeric</td>
<td>Total diesel consumption in diesel liter equivalent (DLE) – convert to diesel gallon equivalent (DGE)</td>
</tr>
<tr>
<td>NG_consump_DLEperkwh</td>
<td>DLE/kWh</td>
<td>Numeric</td>
<td>Total NG consumption in diesel liter equivalent (DLE), including converted and loss – convert to diesel gallon equivalent (DGE)</td>
</tr>
<tr>
<td>Engine_load</td>
<td>1</td>
<td>Numeric</td>
<td>Engine load(s) during the operation</td>
</tr>
<tr>
<td>Fuel_efficiency_ZECE</td>
<td>1</td>
<td>Numeric</td>
<td>power out / (NG power in - CH4 loss + diesel power in)</td>
</tr>
<tr>
<td>Diesel_disp</td>
<td>1</td>
<td>Numeric</td>
<td>1-DF diesel rate/DO diesel rate</td>
</tr>
<tr>
<td>Substitution_ratio_corrected</td>
<td>1</td>
<td>Numeric</td>
<td>(NG power in - CH4 loss) / Total Fuel in</td>
</tr>
<tr>
<td>Substitution_ratio_industry</td>
<td>1</td>
<td>Numeric</td>
<td>NG power in / Total Fuel in</td>
</tr>
<tr>
<td>Methane_loss</td>
<td>1</td>
<td>Numeric</td>
<td>Methane out / Methane in (Non-Combusted Methane (NCM) aka “methane slip”)</td>
</tr>
<tr>
<td>ATS</td>
<td>N/A</td>
<td>Category</td>
<td>Aftertreatment system, Y-emissions after ATS; N-emissions before ATS or ATS is not applied</td>
</tr>
<tr>
<td>Emission_GHG</td>
<td>CO2e kg/kWh</td>
<td>Numeric</td>
<td>GHG emission includes CO2, CH4 (GWP=25) and N2O (GWP=298)</td>
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<tr>
<td>Emission_NMHC_NOx</td>
<td>g/kWh</td>
<td>Numeric</td>
<td>NMHC emissions + NOx emissions</td>
</tr>
<tr>
<td>Emission_CO</td>
<td>g/kWh</td>
<td>Numeric</td>
<td>CO emission</td>
</tr>
</tbody>
</table>
Supervised Learning

- Linear Regression “supervised learning”
- Selected features
- Randomly split 80% data for modeling, 20% for testing
- 1,000 random scores (neural regression 100 random scores)
- **MARE:** Mean Absolute Relative Error
  - e.g. a ± b%
    
    \[ MARE = \frac{\sum |\text{Predicted value} - \text{Test value}|}{\text{Test value} \times \text{Number of test value}} \]

- **RMSE:** Root Mean Squared Error
  - e.g. a ± c
    
    \[ RMSE = \sqrt{\frac{\sum (\text{Predicted value} - \text{Test value})^2}{\text{Number of test value}}} \]
# Prediction Summary Example

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Representative Value*</th>
<th>Best Prediction MARE**</th>
<th>Best Prediction RMSE***</th>
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</thead>
<tbody>
<tr>
<td>Fuel efficiency</td>
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<td>0.266</td>
<td>4.3%</td>
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<tr>
<td>Diesel displacement</td>
<td>1</td>
<td>0.604</td>
<td>7.2%</td>
<td>0.055</td>
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<tr>
<td>Substitution ratio</td>
<td>1</td>
<td>0.698</td>
<td>4.8%</td>
<td>0.044</td>
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<tr>
<td>GHG emission</td>
<td>CO2e kg/kWh</td>
<td>1.880</td>
<td>3.9%</td>
<td>0.095</td>
</tr>
<tr>
<td>NMHC+NOx w/o ATS</td>
<td>g/kWh</td>
<td>10.194</td>
<td>10.4%</td>
<td>1.15</td>
</tr>
<tr>
<td>NMHC+NOx w/ ATS</td>
<td>g/kWh</td>
<td>5.123</td>
<td>10.4%</td>
<td>0.61</td>
</tr>
<tr>
<td>CO w/o ATS</td>
<td>g/kWh</td>
<td>23.65</td>
<td>4.8%</td>
<td>1.36</td>
</tr>
<tr>
<td>CO w/ ATS</td>
<td>g/kWh</td>
<td>0.217</td>
<td>21.4%</td>
<td>0.063</td>
</tr>
</tbody>
</table>

*Mean value in database
**MARE: Mean Absolute Relative Error
***RMSE: Root Mean Squared Error
Application Scenarios

• Optimized
  – Best accuracy

  Optimized features → Model based on optimized features → Prediction

• Customized
  – Best practice

  Customized features → Model based on customized features → Prediction
Application Scenarios

How to use data in LCA (example)

• LCA Software
  – Processes
  – Energy
  – Fuels

• Carbon Footprint

Life Cycle Inventory

Output (function unit):
1 kWh electricity by dual fuel

Input:
NG at production onshore, diesel, infrastructure

Emissions:
GHG, NMHC+NOx, CO

Description:
Emissions are predicted by activity, RPM, loading, NG and diesel consumption, etc.
Additionally...

Prediction is a powerful tool, but still involves some uncertainties... not a substitute for field testing, data collection & analysis
Intrinsically Safe Instrumentation

Data Acquisition & Control System
- LabVIEW FPGA
  - Design & developed at HARC
- Records data for fuel flow, air flow, temperatures, pressures, ambient conditions, gaseous emissions & soot
### Dual Fuel Study Parameters

**Gaseous Emissions, Soot, Fuel Consumption, Engine Operation Conditions**

<table>
<thead>
<tr>
<th>Gaseous Emissions</th>
<th>Fuel Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Oxide</td>
<td>Fuel supply Flow</td>
</tr>
<tr>
<td>Ethylene</td>
<td>Fuel Return Flow</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>Diesel Fuel Consumption</td>
</tr>
<tr>
<td>Acetylene</td>
<td>Natural Gas Flow</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td></td>
</tr>
<tr>
<td>Propane</td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
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</tr>
<tr>
<td>Propylene</td>
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<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide</td>
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</tr>
<tr>
<td>Formaldehyde</td>
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</tr>
<tr>
<td>Carbon Dioxide</td>
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<td>Acetaldehyde</td>
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<td>Methane</td>
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<td>Formic Acid</td>
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<td>Ethane</td>
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<tr>
<td>Methanol</td>
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</table>

<table>
<thead>
<tr>
<th>Ambient Conditions</th>
<th>Exhaust Conditions</th>
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</thead>
<tbody>
<tr>
<td>Temperature (C)</td>
<td>Temperature (C)</td>
</tr>
<tr>
<td>Pressure (mbar)</td>
<td>Soot</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>Oxygen</td>
</tr>
<tr>
<td>Dew Point (C)</td>
<td>A/F ratio</td>
</tr>
</tbody>
</table>

**Measurements**

- CO
- NO, NO$_2$ (NO$_x$)
- VOCs (including formaldehyde [CH$_2$O])
- Soot (indicative of PM)
- Non-Combusted Methane (NCM) aka “slip”
- Direct Measurement of Diesel Fuel and Natural Gas Fuel
Thank You

HARC (härk), n.
an independent research hub helping people thrive and nature flourish.

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