Non-Obvious Relational Awareness for Diesel Engine Fluid Consumption

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May 12, 2015

2015 MathWorks
Automotive Conference
Plymouth, Michigan

Agenda

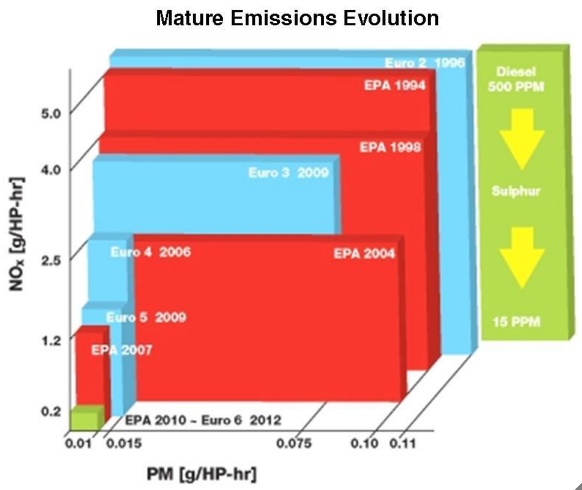
- Introduction to SCR Technology
- Introduction to Cummins version of Non-Obvious Relational Awareness (NORA) Analysis
- Process Flow for NORA Analysis
- Relational Computation
- Example Results
- Summary and Conclusions

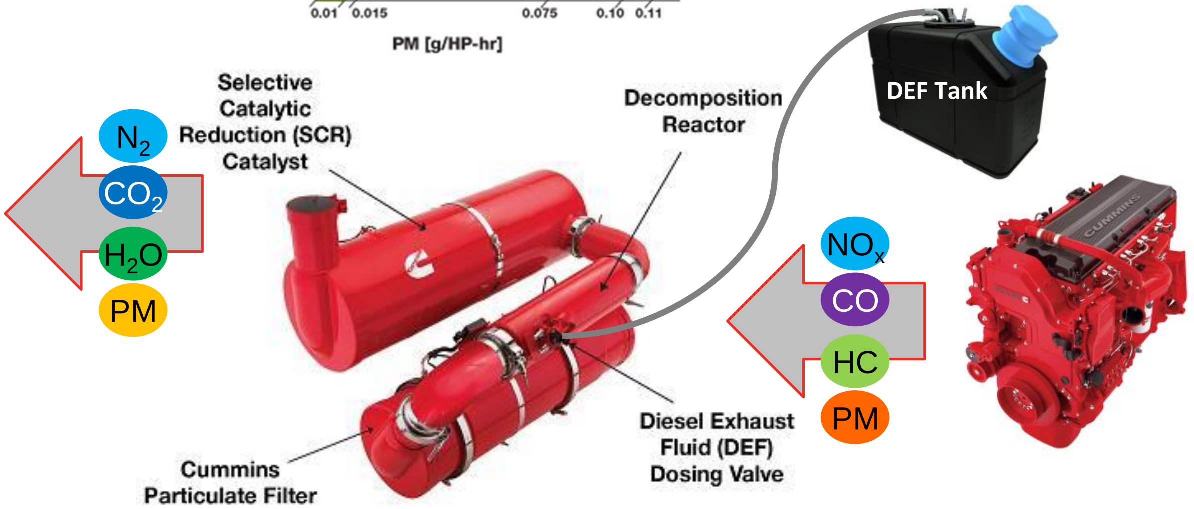
Introduction

- In 2010, Cummins Inc. introduced Selective Catalytic Reduction (SCR) technology to our on-highway diesel engine product line
- SCR technology was chosen to meet stringent 2010 North America EPA emission regulations while providing customers with the most fuel efficient diesel engine product
- SCR technology introduced new terminology governing diesel engine efficiency and performance, FLUID ECONOMY
  - Diesel Fuel + Urea, better known as Diesel Exhaust Fluid (DEF)
- Using MATLAB, Cummins engineers developed analysis tools to capture non-obvious relationships between diesel fuel and DEF consumption compared with total system performance

SCR Technology

- Regulations drive reduction in tailpipe emissions
- Diesel Engine Aftertreatment is needed to meet these regulations





NOx Control (SCR Technology)

- Selective Catalytic Reduction (SCR) is a means of converting nitrogen oxides (NOx) to nitrogen gas (N2) and water (H2O)
- Ammonia (NH3), in the form of Aqueous Urea, is added to the exhaust stream to act as a reductant
- Carbon Dioxide (CO2) is a by-product of the reaction
- This Aqueous Urea solution is commonly called Diesel Exhaust Fluid (DEF)
  - An *eutectic* solution of **32.5%** urea in water
  - Lowest freezing point (-11°C) compared with other concentrations

System Performance

- Prior to production launch in 2010, Cummins sought varying methods to analyze and understand the impact of SCR Technology to overall system performance
- Fluid efficiency was seen as an important factor
  - Combination of both diesel fuel efficiency and DEF efficiency
  - Relation of diesel fuel utilization to DEF utilization

Heavy-Duty Diesel Engine Example:
Annual Miles for Average HD Truck (linehaul) = 120,000 miles
MPG for average HD Truck = 6 mpg
120,000 miles / 6 mpg = 20,000 gallons diesel fuel used per year
DEF Usage at 2% of fuel consumed = 400 gallons of DEF used per year
400 gallons / 20 gallon tank (average size) = 20 DEF fill-ups per year

Introduction to NORA Analysis

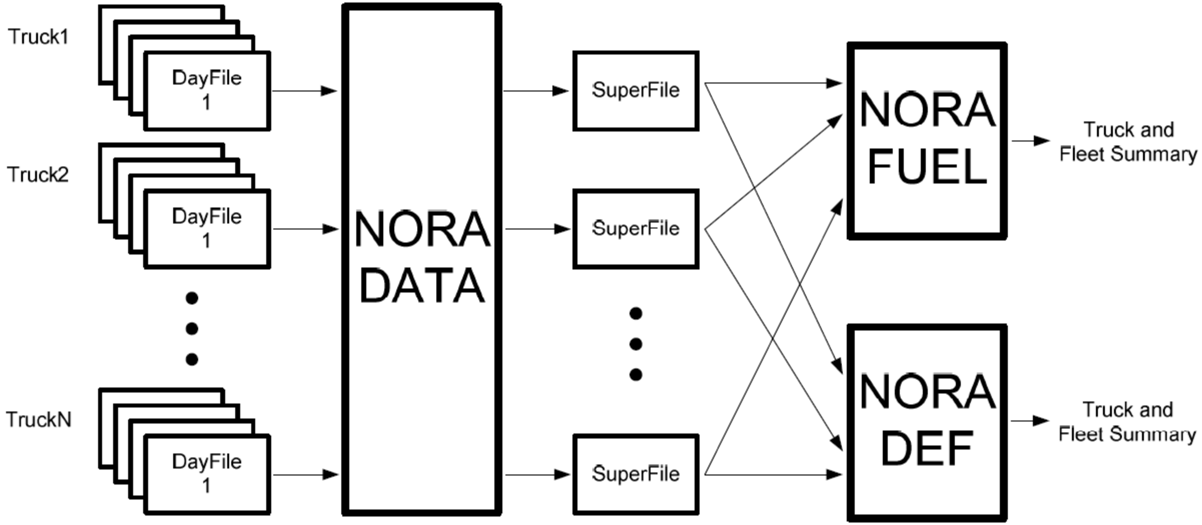
- NORA (Non-Obvious Relational Awareness) data analysis process was originally developed for Cummins Inc. by Thomas A. Grana to assist engineering development teams in understanding failure modes and total system performance impact of SCR from data collected in field tests
- The process utilized MATLAB tools to gather, combine, filter, and reduce large scale data collected from field test vehicles to generate statistical summaries of DEF consumption and fuel consumption
- The input data itself is generated from processes using MATLAB to compile and concatenate time-series data into daily .MAT files

Not the FBI version of NORA

- The concept of non-obvious relational awareness was originally developed by Jeff Jonas in 1989 using Entity Analytics to help identify casino fraud
  - Reference to the movie “21” about the infamous card counting “MIT Blackjack Team” that beat Atlantic City and Las Vegas casinos during the 1980’s
- The NORA concept is used by Homeland Security, FBI, and other law enforcement agencies to identify and apprehend criminals
- The Cummins Inc. version of NORA applies similar theory to highlight non-obvious relationships in field test data using MATLAB as the foundation for code generation and data mining

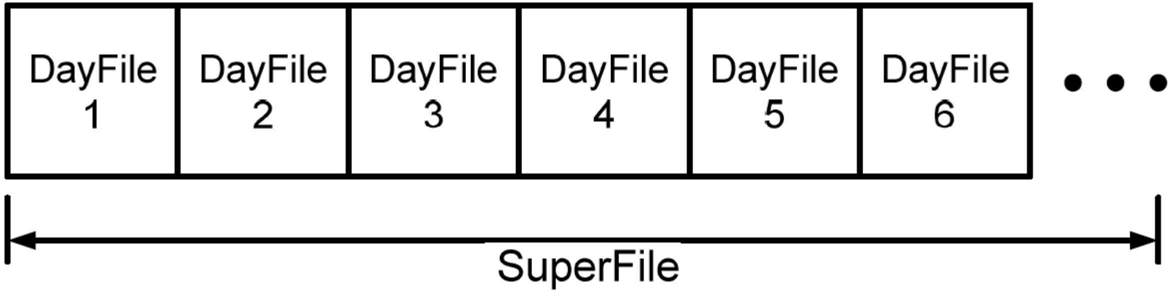
Process Flow for NORA Analysis

- Reduce multiple truck data files into individual “super” files
- Calculate and reduce Fuel Consumption Data
- Calculate and reduce DEF Consumption Data



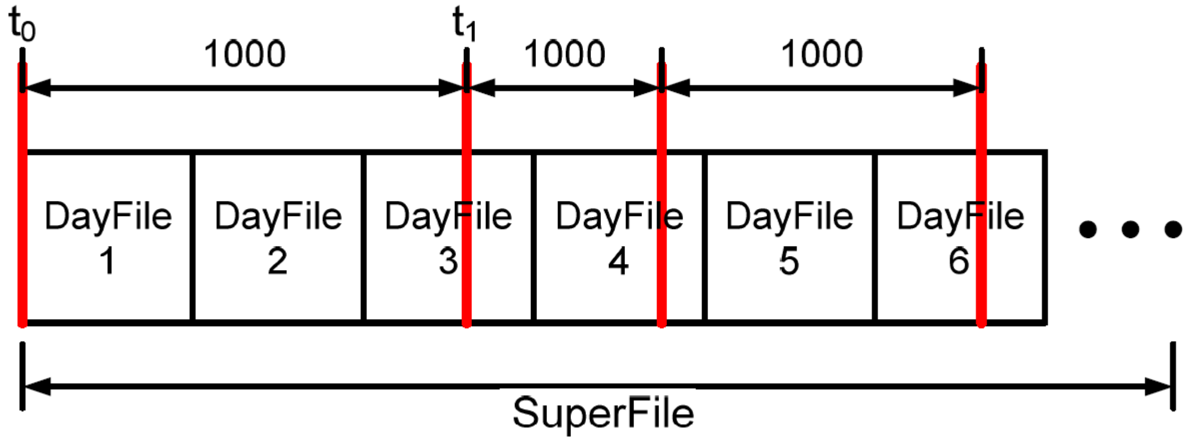
Using MATLAB

- Cummins Inc. collects over 1000 channels of data per field test vehicle over a 24 hour period
- Using MATLAB and NORA process, data is reduced to a much smaller set and then concatenates days together to form a "SuperFile"



DEF Consumption Calculations

- NORA loops through each truck data file to calculate average DEF consumption observations for statistical summaries and plotting
- New observations are saved for each 1000 mile segment travelled**



** Coincides with the approximate interval over which an operator will make an observation at a tank refill

DEF Consumption Calculations

- Basic formulae summarized
- Programmed into MATLAB
- Utilize available channels within data collected

$$Distance\ [mi] = K_1 * \int Vehicle\_Speed \left[\frac{km}{hr}\right] * dt[sec]$$

$$K_1 = \frac{1}{1.609}\left[\frac{mi}{km}\right] * \frac{1}{3600}\left[\frac{hr}{sec}\right]$$

$$FuelRate\left[\frac{g}{sec}\right] = K_2 * Total\_Fueling\left[\frac{mg}{st}\right] * Engine\_Speed\left[\frac{rev}{min}\right]$$

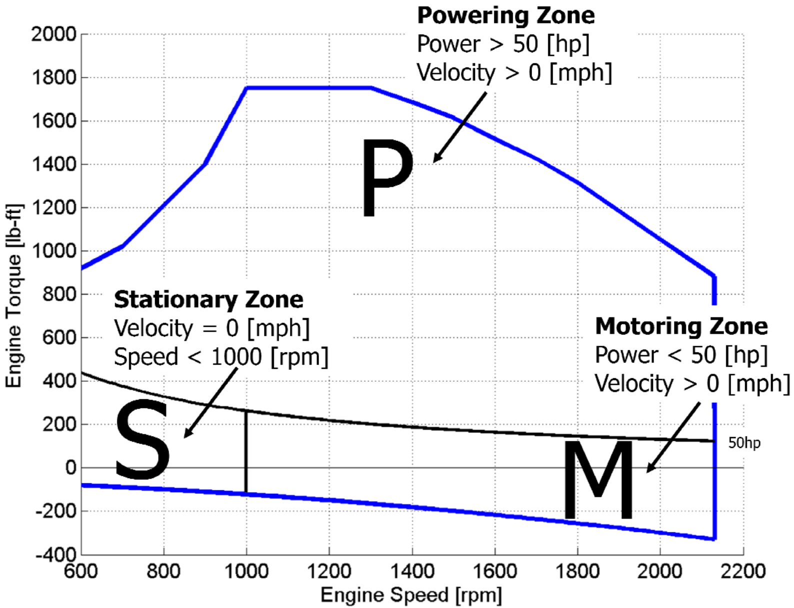
$$K_2 = 3\left[\frac{st}{rev}\right] * \frac{1}{60}\left[\frac{min}{sec}\right] * \frac{1}{1000}\left[\frac{g}{mg}\right]$$

$$TotalFuel[g] = \int_{t_0}^{t_1} FuelRate\left[\frac{g}{sec}\right] * dt[sec]$$

$$TotalDEF[g] = \int_{t_0}^{t_1} DEFRate\left[\frac{g}{sec}\right] * dt[sec]$$

Fuel Consumption Calculations

- NORA loops through each truck data file to calculate average fuel efficiency observations for statistical summaries and plotting
- New observations are saved for each 1000 mile segment travelled**
- Calculation is three zones
  - Powering Zone
  - Stationary Zone
  - Motoring Zone (no calculation made)



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$$TotalFuel[g] = \int_{t_0}^{t_1} FuelRate\left[\frac{g}{sec}\right] * dt[sec]$$

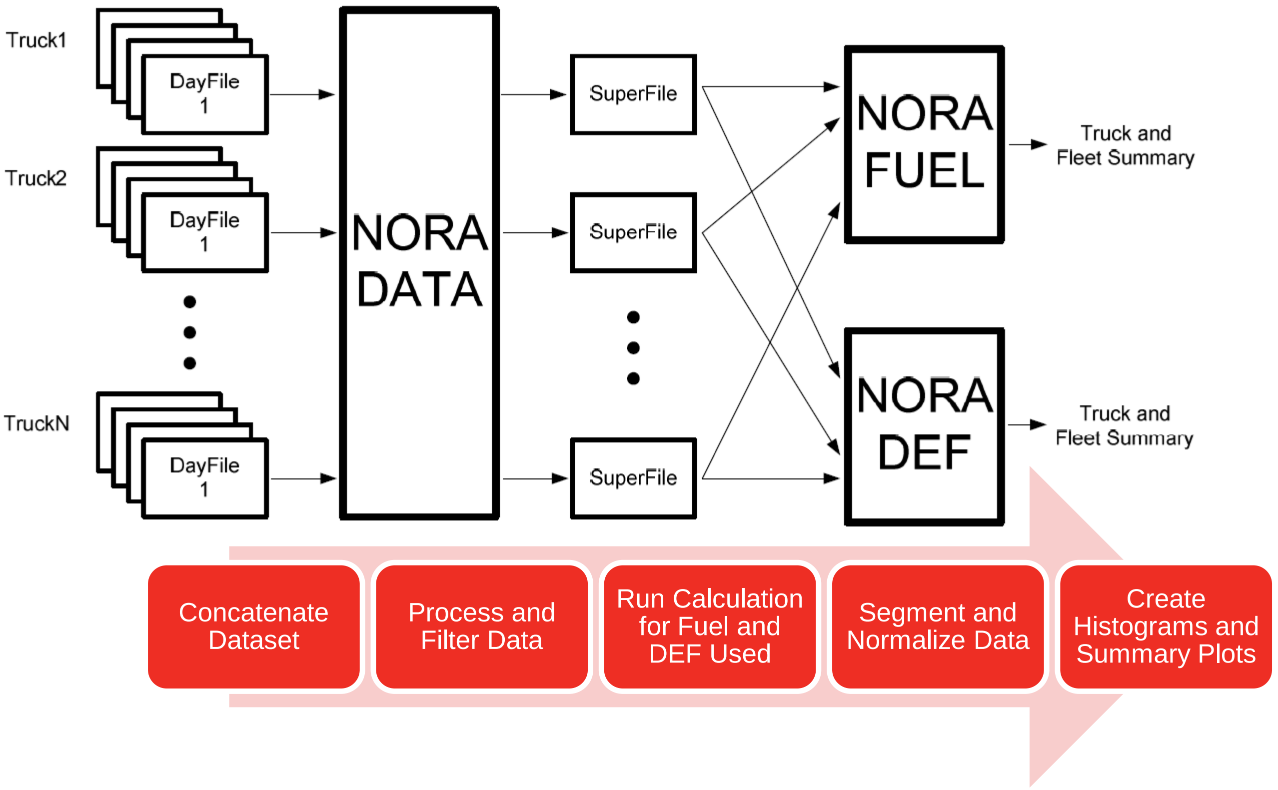
$$Power[hp] = K_3 * Engine\_Torque[Nm] * Engine\_Speed\left[\frac{rev}{min}\right]$$

$$K_3 = \frac{1}{1.3558}\left[\frac{lbft}{Nm}\right] * \frac{1}{5252}$$

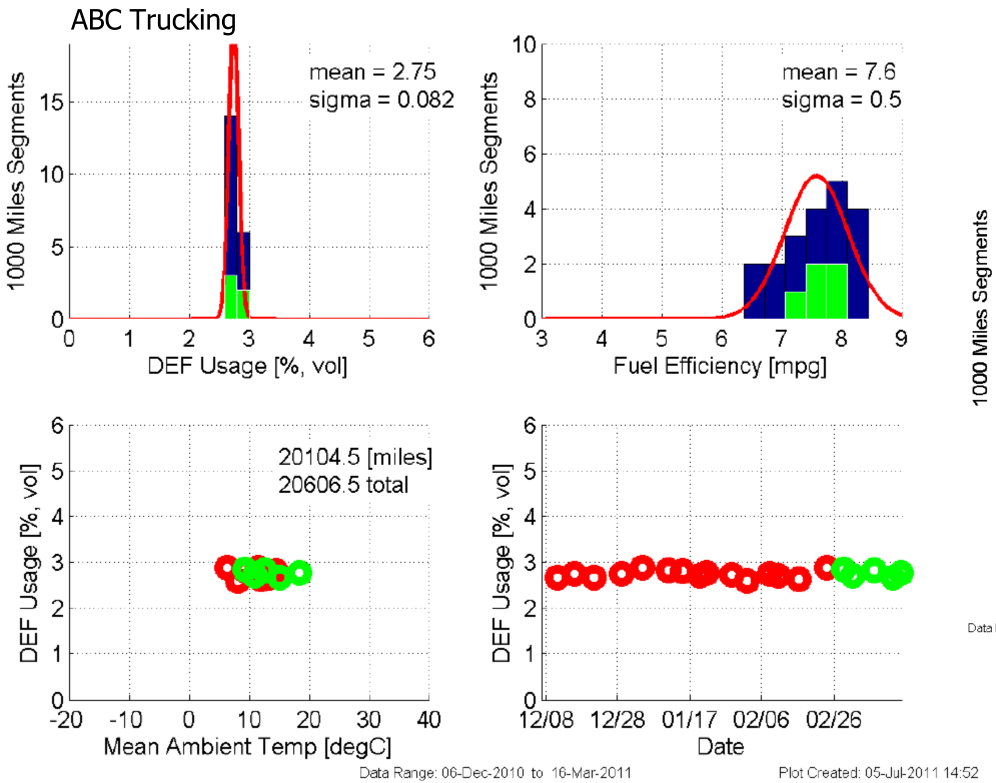
$$CycleWork[hphr] = K_4 * \int_{t_0}^{t_1} Power[hp] * dt[sec] * P(t)$$

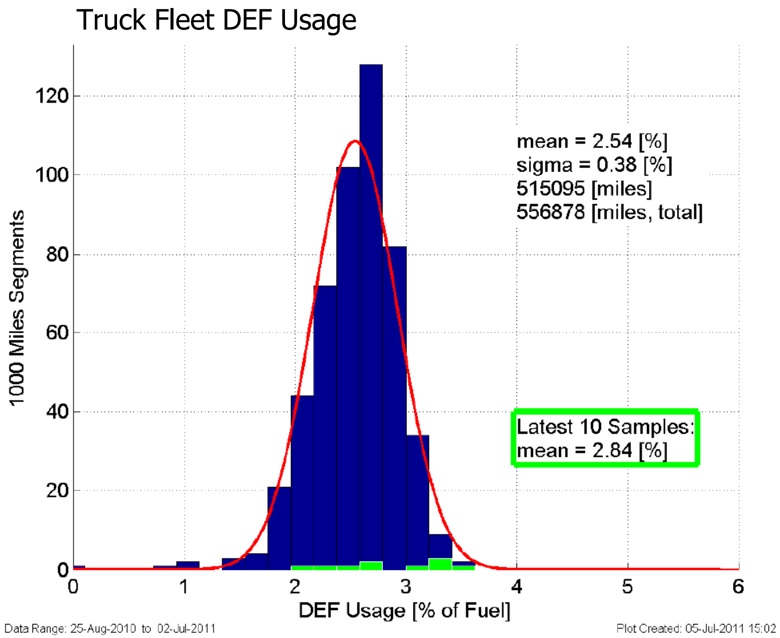
$$K_4 = \frac{1}{3600}\left[\frac{hr}{sec}\right]$$

Bringing It All Together



Example Results

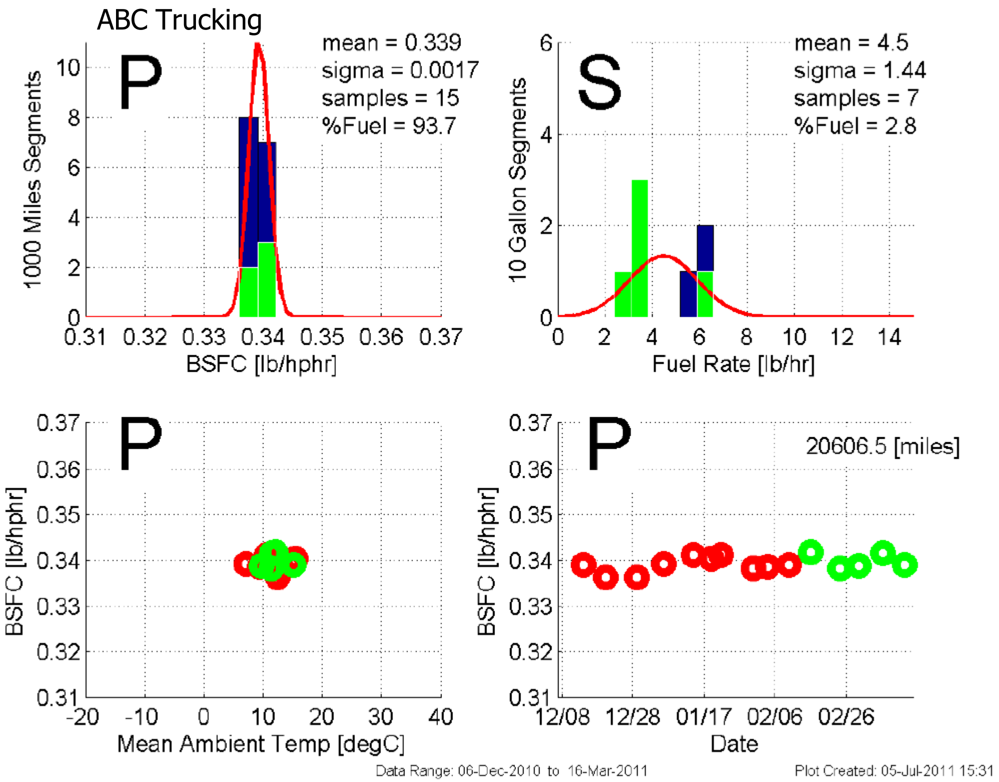


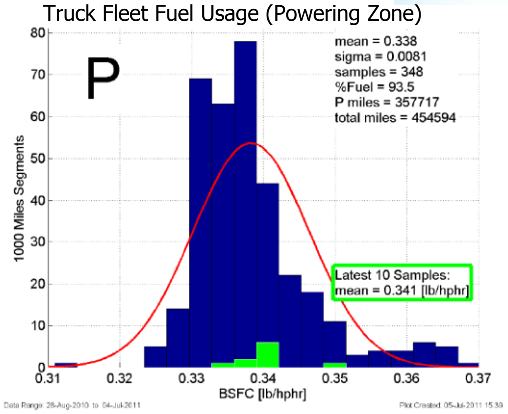


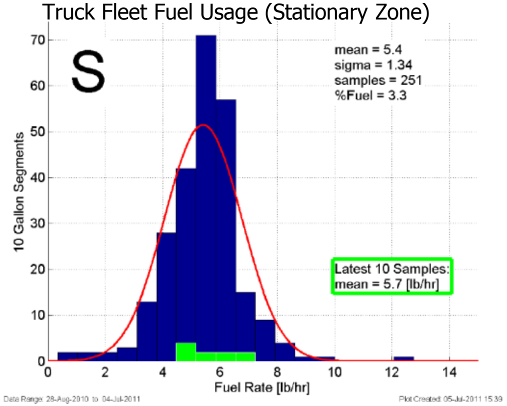
Red = All Samples

Green = Last 10 Samples

Example Results







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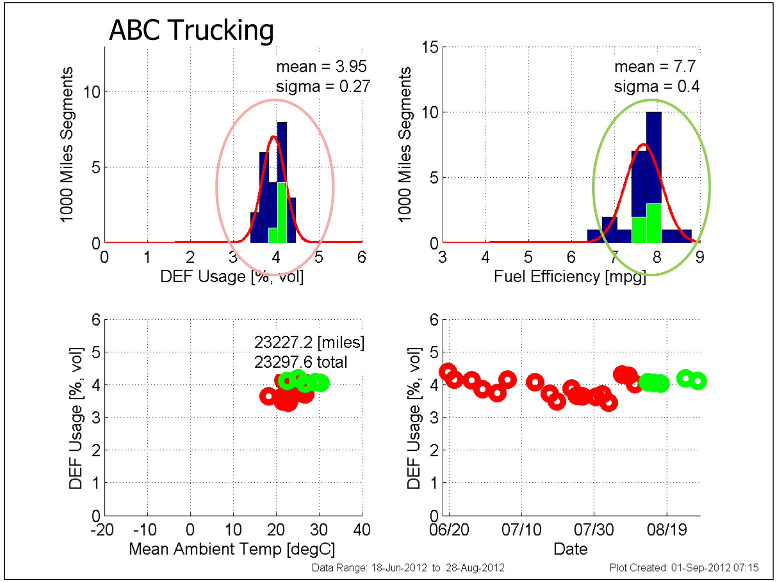
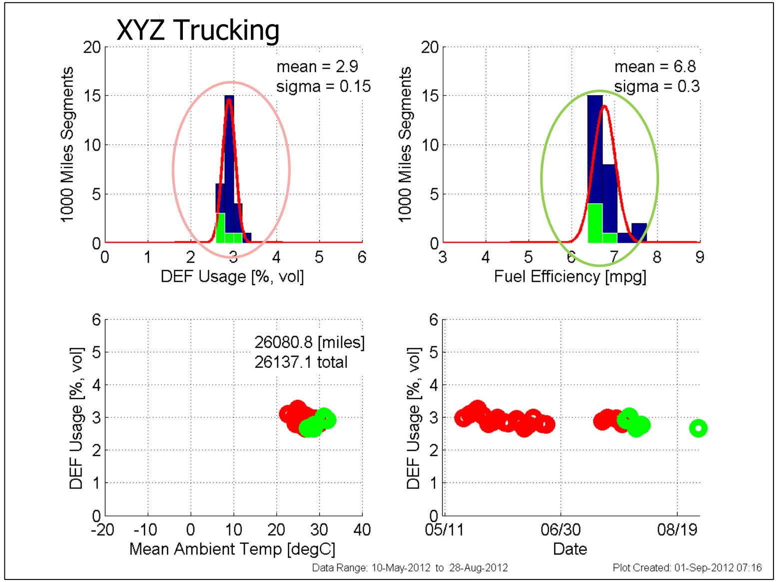
Case Studies

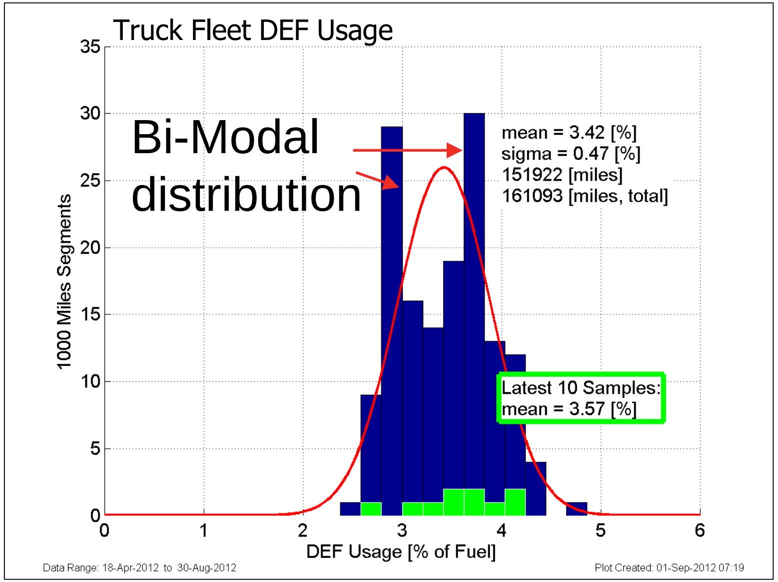
- Utilize NORA Analysis to observe trends amongst similar engines within a population

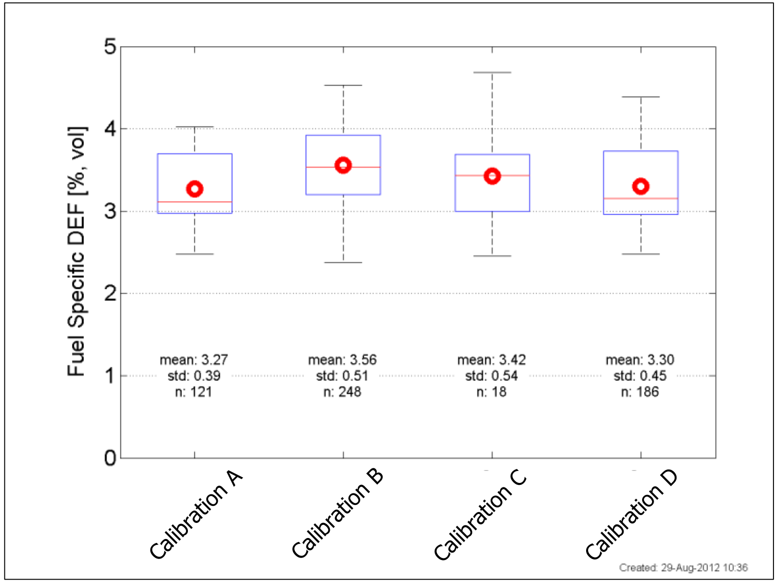




Case Studies

- Utilize NORA Analysis to make observations against fleet performance within field test development time windows

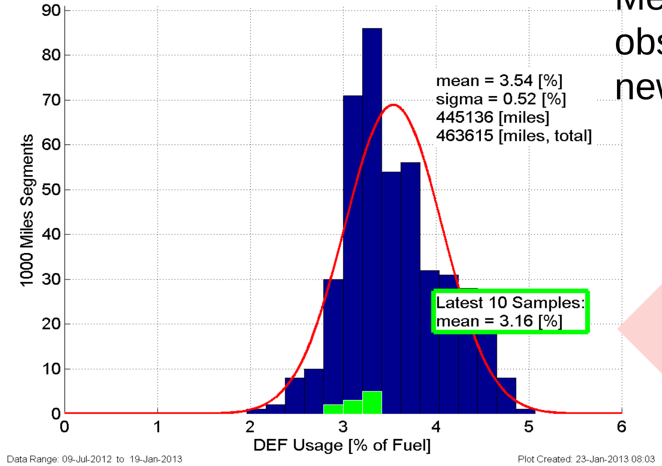




Case Studies

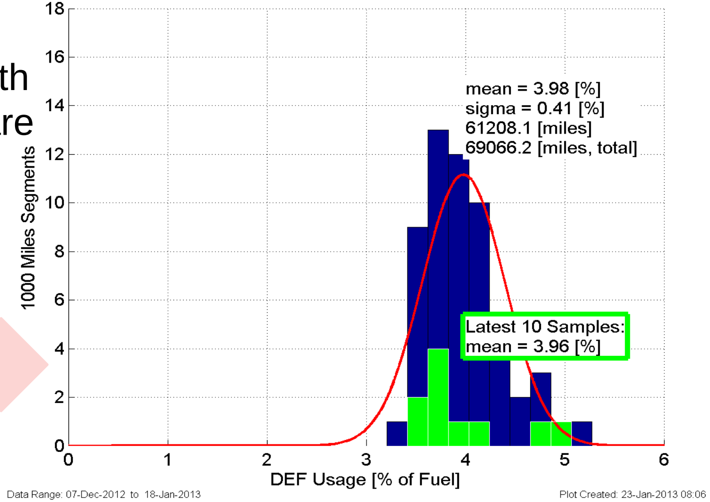
- Utilize NORA Analysis to make observations against specific hardware changes and impact to DEF Usage

Truck Fleet DEF Usage – Hardware Set #1



Mean shift observed with new hardware

Truck Fleet DEF Usage – Hardware Set #2



Potential Cost Avoidance

- Previous Heavy-Duty Diesel Engine example
- Additional assumptions
  - $4.00 per gallon diesel fuel
  - $2.50 per gallon DEF (avg.)
- Using NORA process, 5 mpg and DEF usage of 4% of fuel consumed observed
- Corrective action leads to potential $17,400 cost avoidance per truck per year

Heavy-Duty Diesel Engine Example:
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400 gallons / 20 gallon tank (average size) = 20 DEF fill-ups per year

5 mpg DEF Usage @ 4% of fuel consumed:
120,000 miles / 5 mpg = 24,000 gallons diesel fuel used per year
24,000 gallons diesel fuel used per year x $4.00 per gallon = **$96,000 per year fuel costs**
DEF Usage at **4%** of fuel consumed = **960 gallons** of DEF used per year
960 gallons DEF used per year x $2.50 per gallon = **$2,400 per year DEF costs**
Total cost to customer = $98,400 per year per truck

6 mpg and DEF Usage @ 2% of fuel consumed:
120,000 miles / 6 mpg = 20,000 gallons diesel fuel used per year
20,000 gallons diesel fuel used per year x $4.00 per gallon = **$80,000 per year fuel costs**
DEF Usage at **2%** of fuel consumed = **400 gallons** of DEF used per year
400 gallons DEF used per year x $2.50 per gallon = **$1,000 per year DEF costs**
Total cost to customer = $81,000 per year per truck

Automation and Task Scheduling

- NORA process can be automated utilizing an “executive” script to manage main process calls and data storage locations
- Through Windows, a Task Scheduler can be created to execute all necessary processes as desired by the user
- Currently, this analysis tool is maintained and managed within the engineering community to support analysis as needed
- Future enhancements include,
  - Development of GUI Interfaces to develop NORA as an Application
  - Removal of specific dependencies to allow broad range of applications (Medium-Duty vehicles, Off-Highway applications, etc.)
  - Streamline and Robust programming

Summary and Conclusions

- To assist development engineers with understanding fundamental system performance and trends with SCR technology on diesel engines, Cummins developed an analysis process called NORA (Non-Obvious Relational Awareness)
- Utilizing MATLAB tools and features, NORA integrates physics based equations along with data merging and reduction to produce statistical summaries and plots
- These statistical summaries and plots are used today to assess system behaviors so that Cummins can deliver the best diesel engine and aftertreatment system to the end customer

Many Thanks For Your Attention