Universal Onboard Marine Emission Measurement Protocols

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Advocating the Development of Universal Onboard Marine Emission Measurement Protocols

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Robert Behr and Daniel Gore, U. S. Maritime Administration

Jonathan DeHart, NAVSEA – Philadelphia

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James Corbett, University of Delaware

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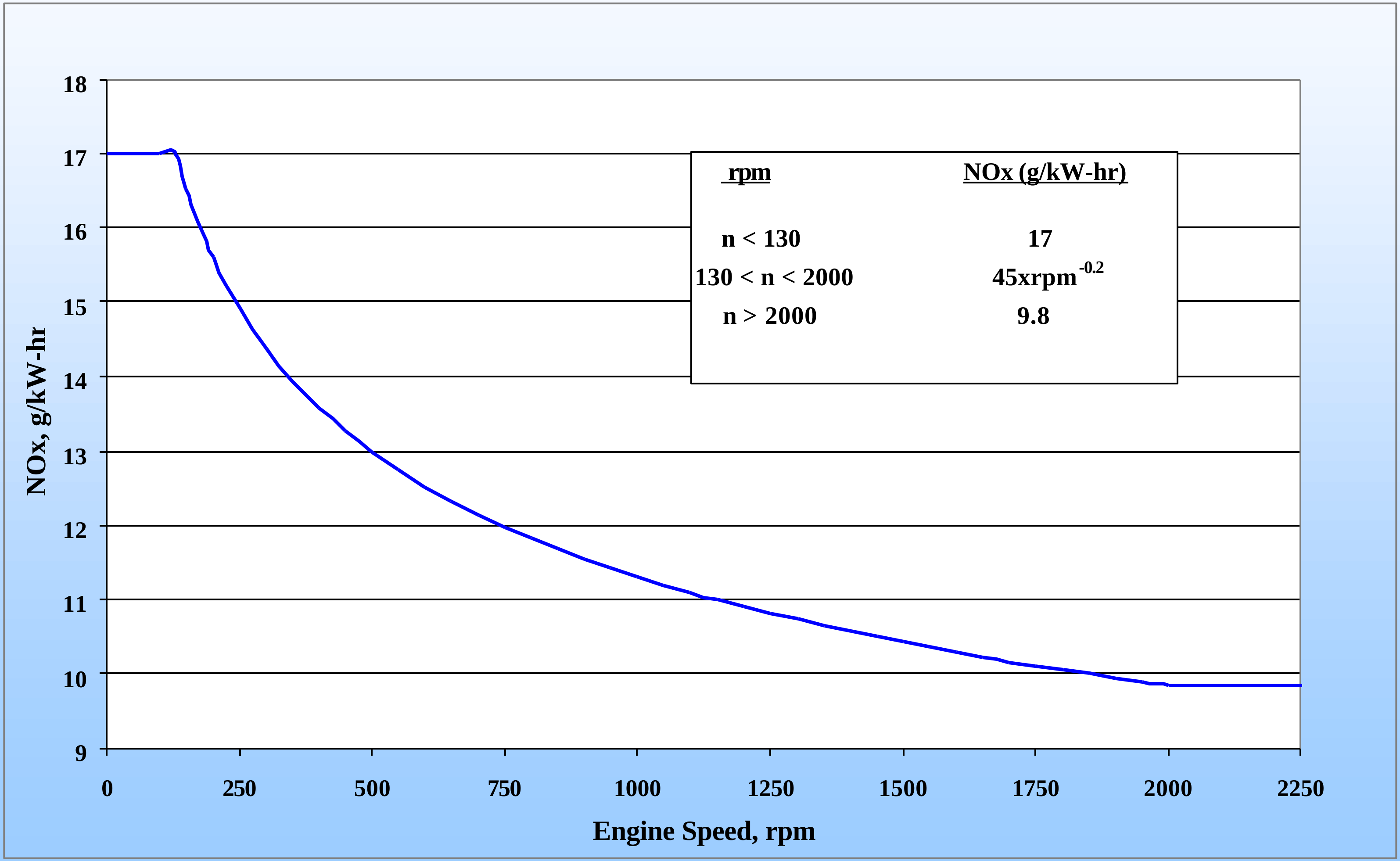
Overview

- Need for Marine Emission Measurement Protocols
- Protocol Content
- Recommendations
- Summary

MARPOL 73/78 Annex VI NO_x Limits (Tier 1)



Need for Marine Emission Measurement Protocols

Background

- Why Onboard Testing?
  - Data not obtainable in test cell
  - Regulatory requirements
  - Identification of most effective technologies
- Uncertainties of Onboard Testing
  - Determining the most suitable test methods
  - Overcoming challenges of marine environment
  - Obtaining sufficient accuracy and repeatability

Scope of Protocol

- Measurement of criteria pollutants
- Rigorous formal testing
- Steady state and transient operation
- Diesel engines driving propellers, generators or waterjets
- Distillate or residual fuel oil

Purpose of In-use Emissions Measurements

- **TECHNOLOGY DEVELOPMENT AND/OR ASSESSMENT**
- **ENFORCEMENT**
- **COMPLIANCE**
- **I/M**
- **SCREENING**
- **INVENTORY**

Protocol Content

Unique Marine Issues

- Environmental
  - Sea
  - Ambient
  - Hull fouling
- Equipment
  - Engine types
  - Wet exhaust installation
  - Fuel
  - Space
- Operational
  - Payload
  - Maneuvering
  - Modes
  - In-service
  - Personnel on board
- Safety
  - Calibration gases
  - Limited ventilation

Methodology

- Type of characterization
  - Raw
  - Dilute
  - Remote
- Measurement
  - Parameters
  - Corrections
  - Locations
  - Accuracy & repeatability
- Data end use
  - Representative operation
  - Modeling
  - Inventory and engine modification reductions
  - Durability of emission controls
- Emission constituents
  - Currently regulated
  - Amenable to targets for future regulation
- Units of objective variables
  - Mass emissions
  - Brake power specific basis

Operating Conditions & Cycles

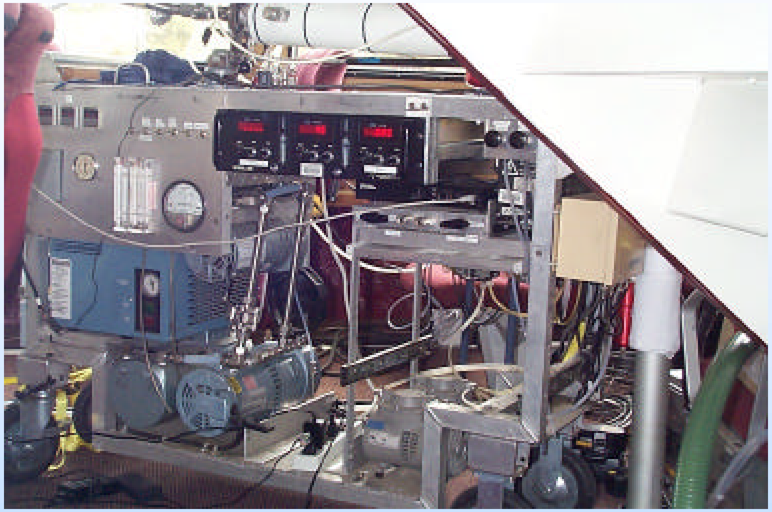
- Factors critical to data utility
  - Reproducible
  - Representative

- Types of operation
  - Steady-state
  - Transient

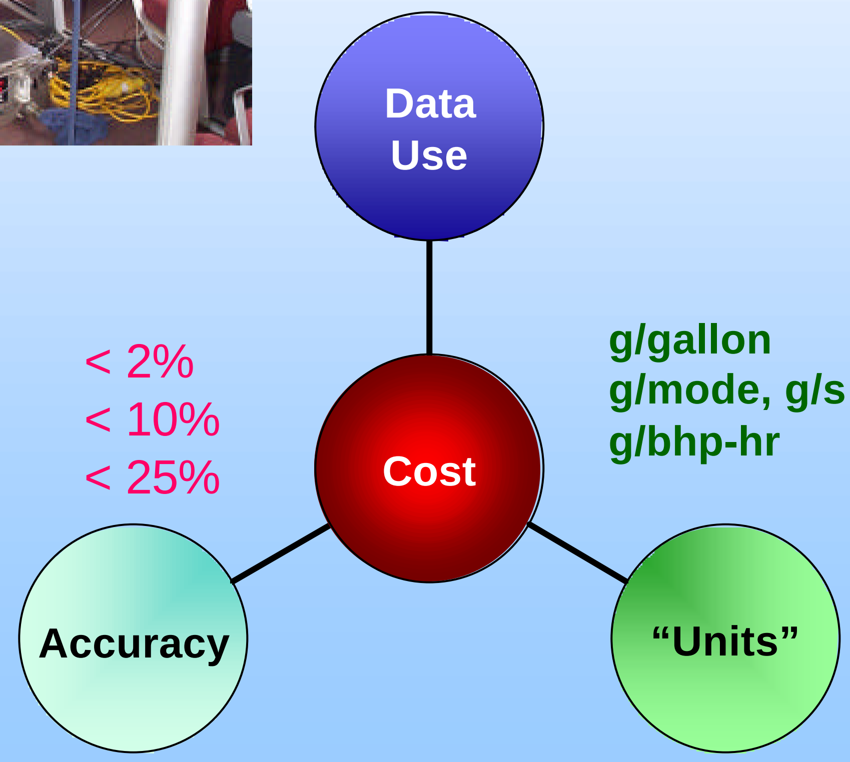
- Options for reproducing transient operation
  - Estimation
  - Modeling
  - Measurement

- Challenges
  - Repeating operating conditions
  - Representing typical operation
  - Transient operation testing

Instrumentation Requirements



Good Neighbor Demonstration Program
SIPs
Emissions Credits



Instrumentation Requirements

Instrumentation - Methods

Constituent	Sampling Method	Detection Method	
		Primary	Alternate
THC	Continuous	FID	
NMHC	Continuous / Bag	FID w/ Cutter / GC, GCMS	
CO	Continuous or Bag	NDIR	NDUV
CO_2	Continuous or Bag	NDIR	NDUV
NOx	Continuous	Chemiluminescence	Zirconia Oxide
TPM	Dilute w/ Integrated Filter	Mass	
Aldehydes	Dilute w/ Integrated DNPH	Extraction	
NO_2	Continuous or Integrated		DNPH, NDUV, TDLAS
N_2O	Continuous or Integrated		NDUV, TDLAS, Photo-acoustic
Ammonia	Continuous or Integrated		NDUV, TDLAS, Photo-acoustic
VOC	Dilute Bag or Canister	GC, GCMS	
SVOC	Dilute w/ Filter and PUF/XAD	Extraction	
SOF	Dilute w/ Filter	Extraction	
PAH, n-PAH	Dilute w/ Filter and PUF/XAD	Extraction	
PM10, PM2.5, …	Dilute w/ Filter	Mass	
Particle Sizing	Dilute	SMPS	

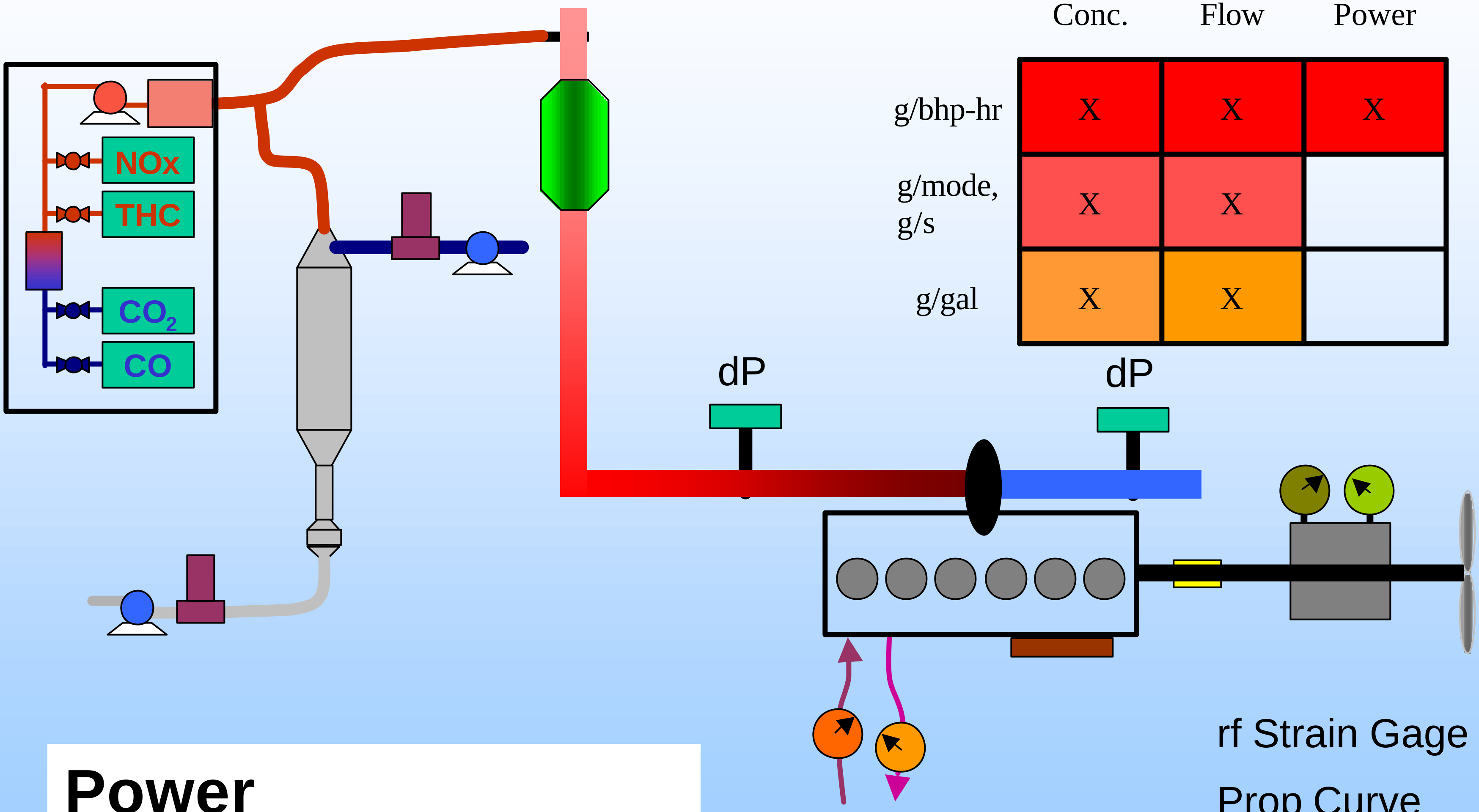
Instrumentation

Complexity →

Cost ↑

	Conc.	Flow	Power
g/bhp-hr	X	X	X
g/mode, g/s	X	X	
g/gal	X	X	

Instrumentation



	Conc.	Flow	Power
g/bhp-hr	X	X	X
g/mode, g/s	X	X	
g/gal	X	X	

Power

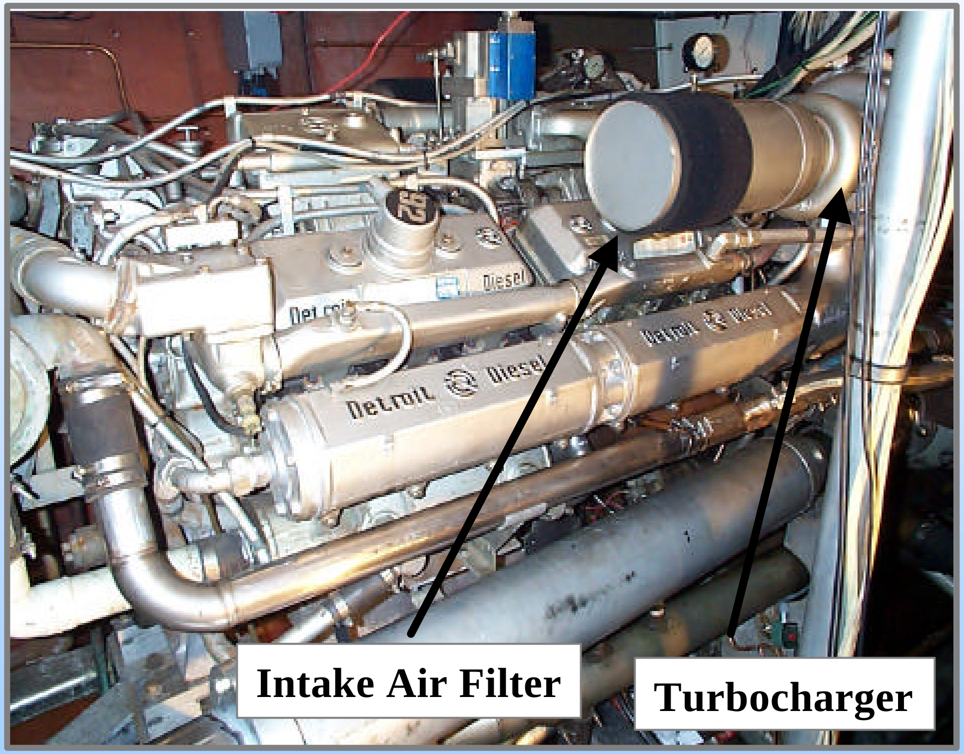
rf Strain Gage

Prop Curve

Gen Set

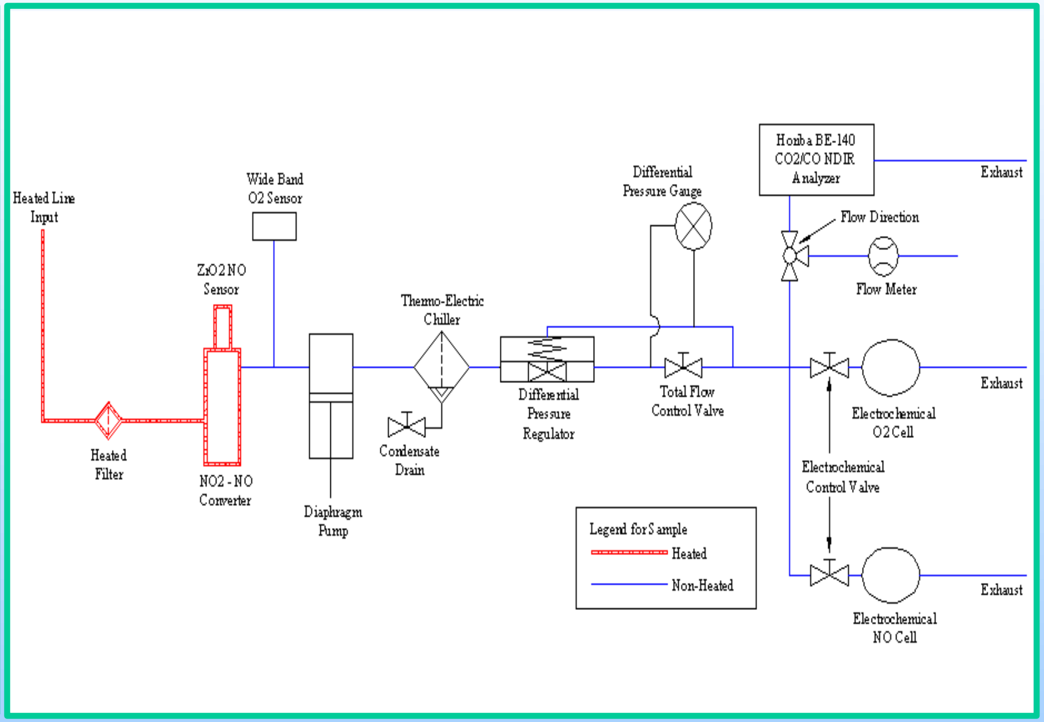
ECU

Test Engine



Engine Detail	Specification
Engine Manufacturer	Detroit Diesel Corporation
Engine Model	12V92
Model Year	1981
Engine I.D.	12VF002734.5.0.2A83804
Displacement	18.1 liters
Power Rating	805 kW @ 2300 rpm
Configuration	12 cylinder V
Bore (m) x Stroke (m)	0.12 m x 0.13 m
Induction	Turbocharger with Blower
Fuel Type	Diesel
Engine Strokes per Cycle	Two
Injection	Mechanical

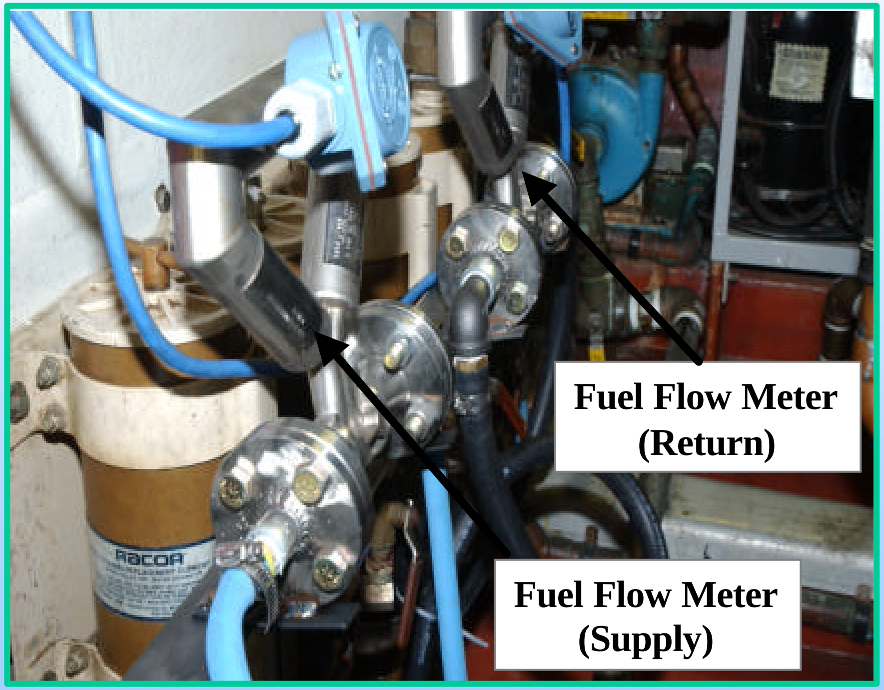
Mobile Emissions Measurement System (MEMS)

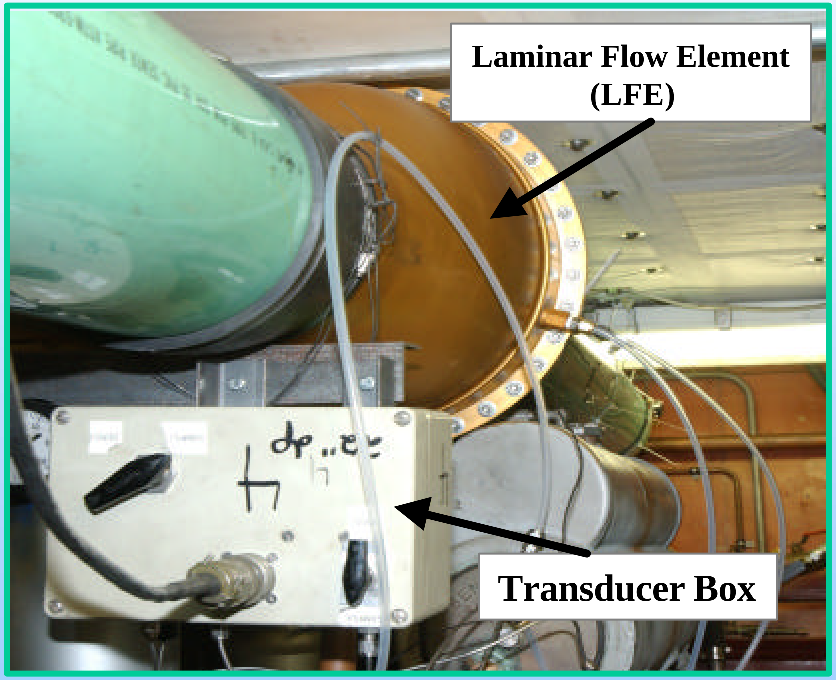


MEMS DAQ and Emissions Box

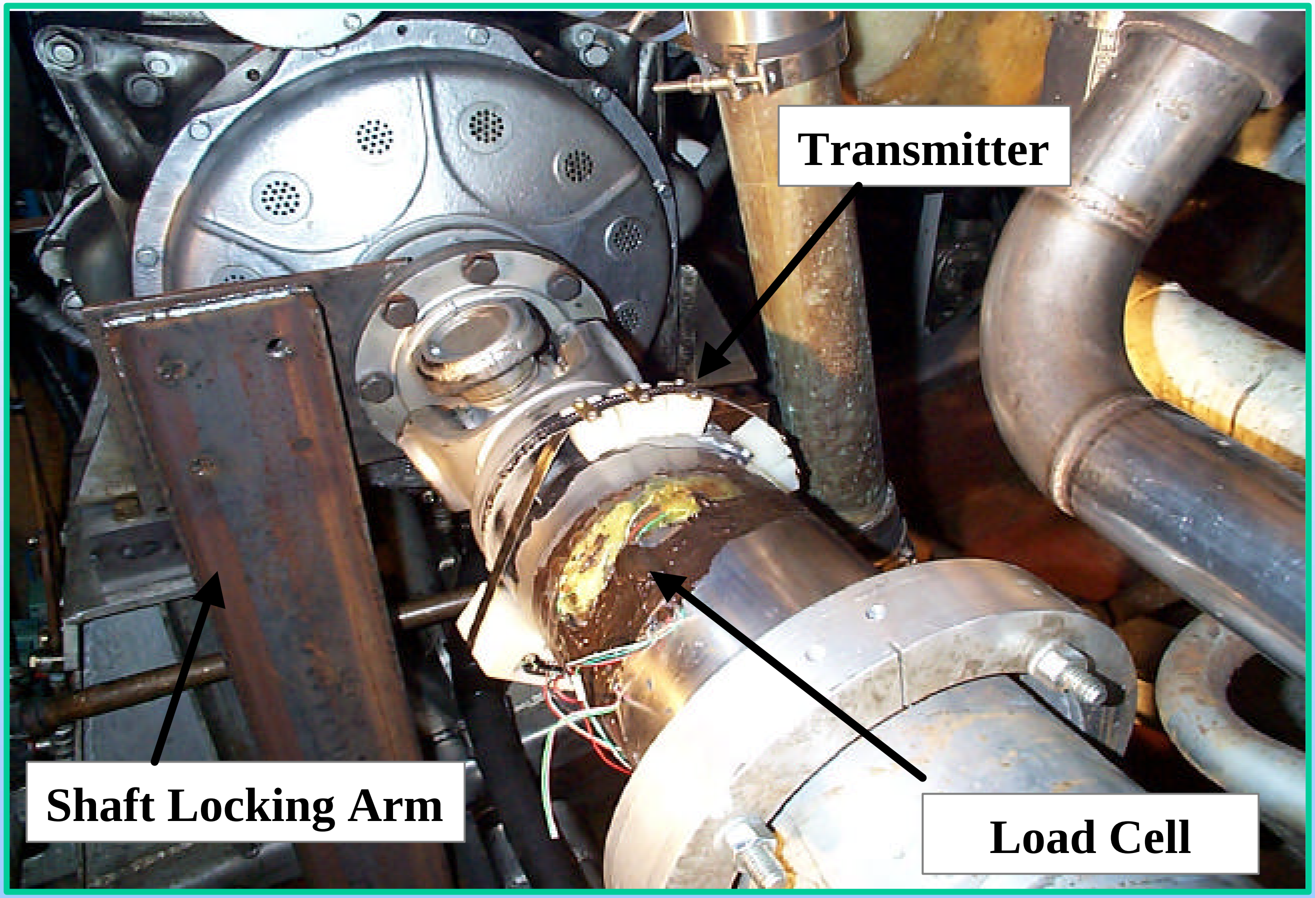
MEMS Sampling System

Fuel Flow and Intake Air Flow Measurements





Torque Measurements



Elizabeth River Ferry Project

- MV James C. Echols (JCE)
  - Twin Cat 3406-G, natural gas fueled engines
- MV Elizabeth River II (ERFII)
  - Twin Detroit Diesel 671 diesel fueled engines

<u>MOBILE SOURCE</u> EMISSIONS REDUCTION CREDITS (MERC)
(Source: NESCAUM)

$$MERC_{pollutant} = (CL - FSAF)*\%\ Reduction*CF_{bhp\text{-}hr/mile}*N_{vehicles}*FM*FMWD*CF$$

where:

CL = The original EPA new engine certification level (g/bhp-hr) of the engine family.

FSAF = The Fuel sulfur adjustment factor. For some older engine families certified with high sulfur fuel, this amount CL has already been reduced due to use of low sulfur fuel. For all pollutants except PM, FSF= 0

%Reduction = The effectiveness of the aftermarket retrofit equipment expressed as a fraction. The value is always between 0 and 1.

$CF_{bhp\text{-}hr/mile}$ = This is the factor to use when converting from g/bhp-hr to g/mile. The appropriate conversion factor will be calculated by multiplying fuel economy by fuel use divided by brake specific fuel consumption.

$N_{vehicles}$= The number of vehicles with the same emissions certification numbers.

FM = The remaining average vehicle mileage. This value represents the average expected vehicle life remaining until the fleet is retired or overhauled, whichever occurs first.

FMWD = The fraction of mileage within the requesting district. This value is always between 0 and 1.

CF_{units} = $1.1x10^{-6}$ tons/gram or .0000011 tons/gram The appropriate conversion factor that converts the calculated reductions from grams into tons.

FUEL SULFUR ADJUSTMENT FACTOR

FSAF= The fuel sulfur adjustment factor (g/bhp-hr).

An engine originally certified prior to 1994 model year, may have been certified with fuel, which contains a higher sulfur content than currently available fuels. A heavy-duty diesel engine which is currently being fueled with a lower sulfur fuel than the fuel with which it was originally certified, may already be emitting significantly less PM than the original certification level documented. In this case, the baseline PM emission level needs to be adjusted according to the fuel sulfur adjustment factor.

For HC, CO, or NO_x the FSAF always equals 0. For PM the value is calculated as follows:

$$FSAF = BSFC * 0.0917 * (FSF_{cert} - FSF_{in\text{-}use})$$

Where,

BSFC = The brake specific fuel consumption of the engine family in units of g/bhp-hr.

FSF_{cert}= The fuel sulfur fraction of the fuel used to certify the engine family. Typical value = .002(.2%)

$FSF_{in\text{-}use}$= The fuel sulfur fraction of the fuel currently used with the fleet. Typical value = 0.0005(0.05%)

CORRECTION FACTOR (g/bhp-hr to g/mile)

CF [bhp-hr/mile] = [Density (lb/gal)]/[BSFC (lb/bhp-hr)*FE (mile/gal)]

where,

BSFC = Brake specific fuel consumption
FE = Fuel economy

MARINE EMISSIONS REDUCTION CREDITS (MERC)

Activity Metric:	**Mass of fuel burned**
	Other possibilities: Time of Operation
Activity Level:	**Quantity of the activity metric**
Emission Factor:	**grams/unit activity level**

<u>MARINE</u> EMISSIONS REDUCTION CREDITS (MERC)

PROPOSED METHOD

$$MERC = [E_{baseline} - E_{retrofit}] * N_{vessels} * FC * FCWD * CF_{units}$$

where,

$E_{baseline}$ =	Mass emission rate of a pollutant, from baseline tests, in g/kg of fuel
$E_{retrofit}$ =	Mass emission rate of a pollutant, from a retrofit, in g/kg of fuel
$N_{vessels}$ =	The number of vessels with the same emissions certification numbers
FC=	Total fuel consumed (in kg)
FCWD=	Fraction of total fuel that was consumed within the requesting district/area
CF_{units}=	$1.1x10^{-6}$ tons/grams
MERC =	in tons of pollutant

The difference of the baseline and retrofit data will provide conclusive data on NOx and PM reductions.

Concentration Measurement Based Methodology COMPLIANCE FACTOR Approach

(Developed for CARB on a Recently Completed Study on Portable and Stationary Engines)

- Capable of monitoring compliance with existing emission standards for on-highway, and non-road engines, including stationary and portable engines operating under "real world" conditions.
  - This method will be cost-effective, simple, accurate, precise, and significantly less intrusive.
  - Uses only concentration values of NO_x (or any other pollutant) and CO_2 to determine compliance with emission standards.

COMPLIANCE FACTOR Approach

- Brake-Specific Emissions:

$$\frac{NO_x\ (g/\ \cancel{bhp\text{-}hr}\ )}{CO_2\ (g/\ \cancel{bhp\text{-}hr}\ )} \Rightarrow \frac{NO_x\ mass(g)}{CO_2\ mass\ (g)}$$

$MW_{NO_x} \rightarrow$ Molecular Weight of NO_x

$MW_{CO_2} \rightarrow$ Molecular Weight of CO_2

$C\%_{NO_x} \rightarrow$ Concentration of NO_x (ppm) and

$C\%_{CO_2} \rightarrow$ Concentration of CO_2 (ppm).

? $\rightarrow$ Density

$$\frac{NO_x\ mass\ (g)}{CO_2\ mass(g)} = \frac{C\%_{NO_x} \times \dfrac{MW_{NO_x}}{\cancel{Corr.\ factor\ for\ ?}} \times \cancel{Volume}}{C\%_{CO_2} \times \dfrac{MW_{CO_2}}{\cancel{Corr.factor\ for\ ?}} \times \cancel{Volume}}$$

COMPLIANCE FACTOR Approach

- Fuel-Specific Emissions:

$$\frac{NO_x \text{ mass}}{\text{Fuel mass}} = \frac{NO_x \text{ mass}}{\text{mass of C} + \text{mass of H}}$$

Substituting for the mass of C and mass of H expressions using the equation for carbon balance, the fuel specific emissions ratio for NO_x finally reduces to

$$= \frac{\%C_{NO_x} \times MW_{NO_x}}{(12.011 + 1.008 \times \alpha) \times \%C_{CO_2}}$$

COMPLIANCE FACTOR Approach

- Define Compliance Factor F:

$$F = \frac{I}{C}$$

Where,

I (In-field ratio) is the ratio of NO_x to CO_2 mass emissions and may be obtained using either the brake specific or the fuel specific relation.

C (Certification Ratio) is the ratio of brake-specific NO_x to brake-specific CO_2 mass emissions from FTP or ISO 8178 test cycle (as appropriate). May be obtained either from the manufacturer or from laboratory evaluation.

Approach

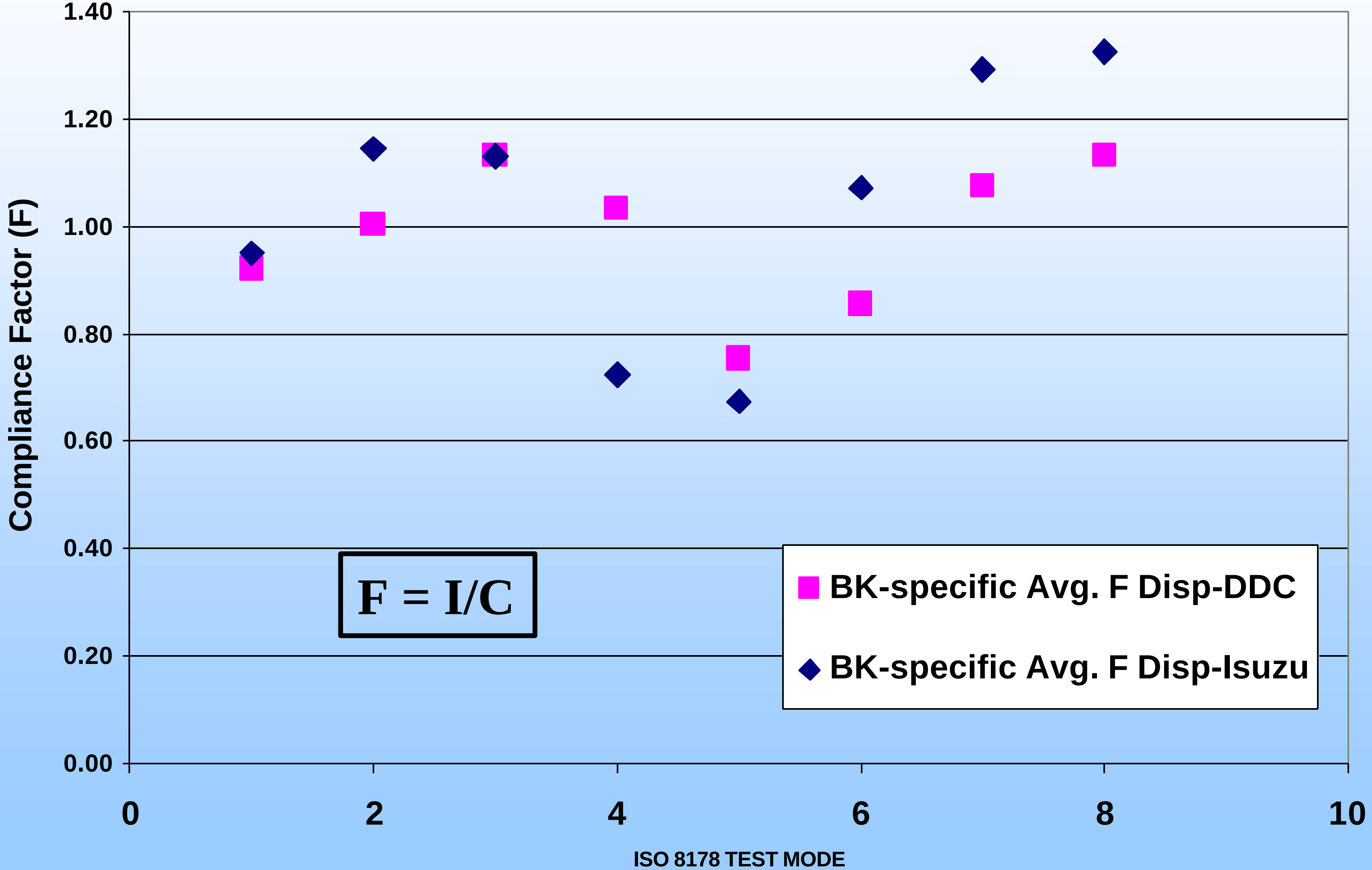
Summary:

- Acquire certification data (ISO 8178, or FTP data; or any other cycle as appropriate).

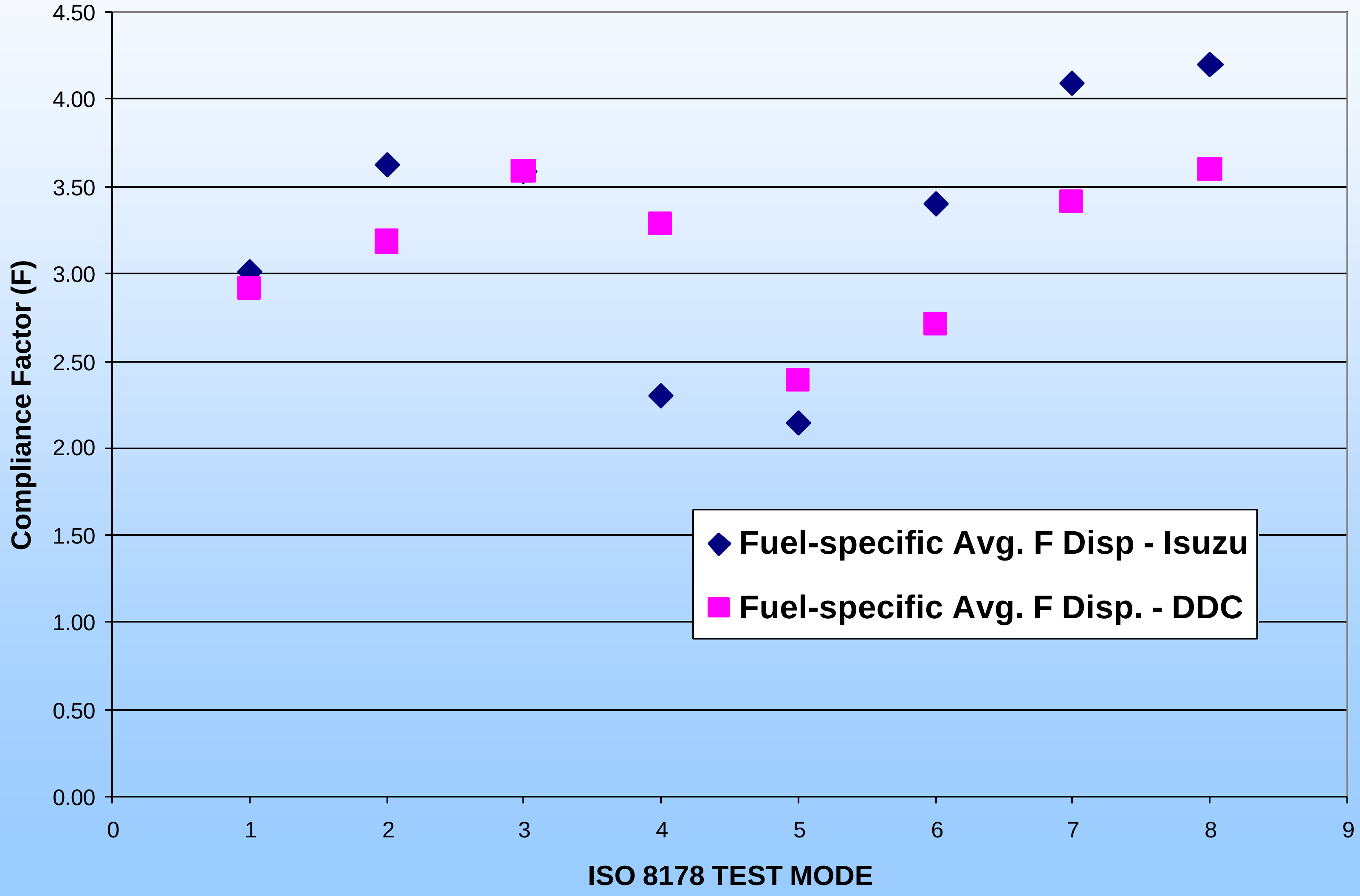
- Measure raw exhaust concentrations of NO_x (and other pollutants as required) and CO_2 emissions by using an available portable emission measurement system.

- Calculate Compliance Factor, F using the pollutant concentrations.

Values of Compliance Factor F
Isuzu C240, DDC Series 60 Engines
Certification Ratio, F Obtained Using the ISO 8178 Test Cycle
In-field Ratio, I Obtained Using The CO_2 Concentration Data.



Values of Compliance Factor F
Isuzu C240, DDC Series 60 Engines
Certification Ratio, F Obtained Using the ISO 8178 Test Cycle
In-field Ratio, I Obtained Using The Fuel - Specific Relation.

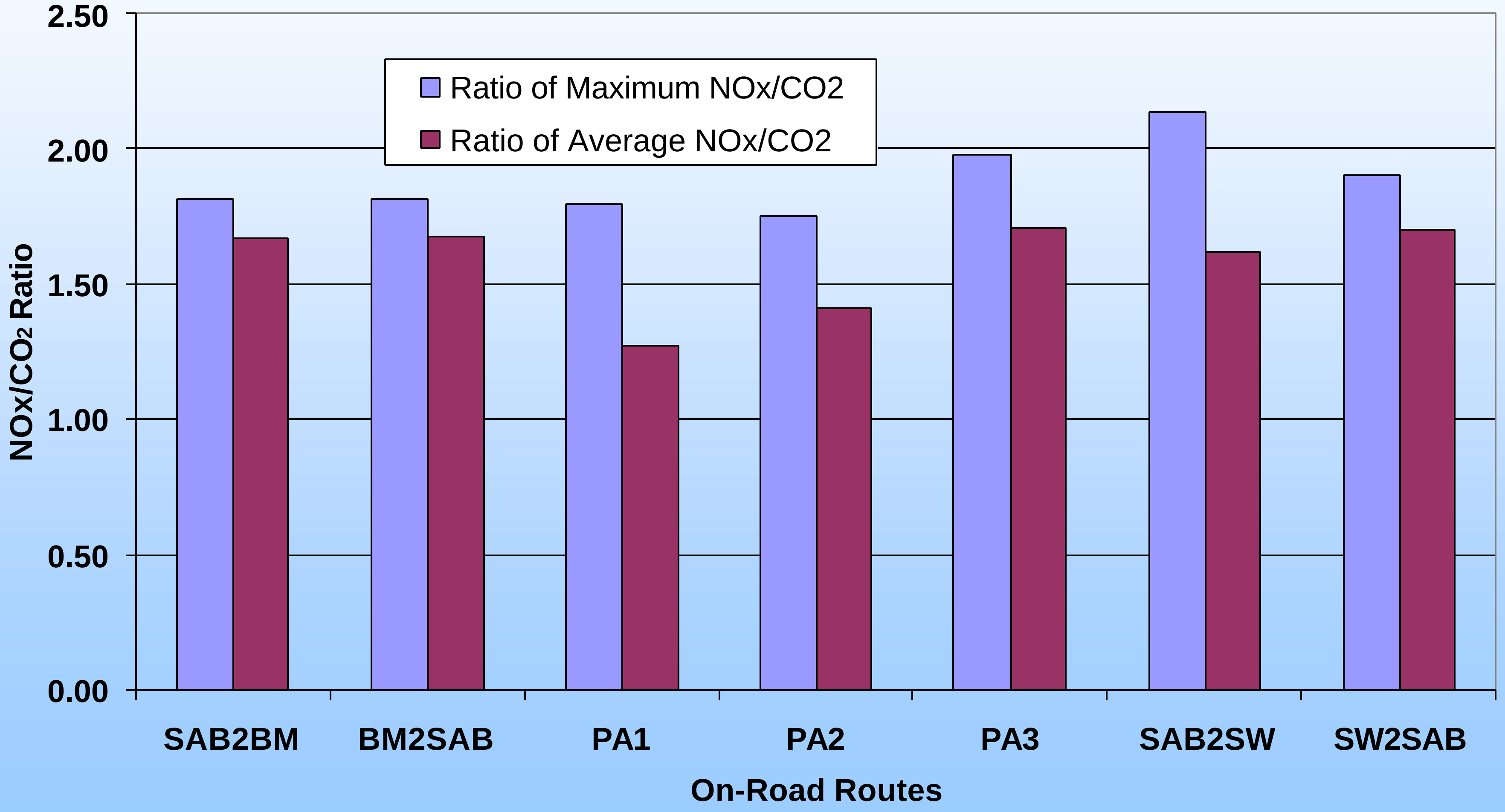


Values of Compliance Factor F (NTE Zone)

Class 8 Tractor; 5.0 g/bhp-hr Engine

Certification Ratio, F Obtained Using Certification data

In-field Ratio, I Obtained Using The CO_2 Concentration Data.



Modifications to Standards

- ISO 8178 Provides for Rigorous Procedure
- Modifications Are Inevitable
- Identify Base Protocol
- Specify Modifications
- Document System Accuracy

Quality Assurance / Control

- Laboratory Verification
  - Vibration Response
  - Emissions
    - Steady State
      - Full Scale CVS
      - Raw with Mini Tunnel
    - Transient
      - Full Scale CVS
      - Time Shift Procedures
- Redundant Systems
  - Flow -Intake/Exhaust vs. Fuel Flow and Emissions
  - Emissions – Electrochemical Cells
  - Power – Manufacturer Data (bsfc)
- System Calibration
  - NIST Traceable
  - In-field Procedures

Reporting

Test Purpose

Engine Information

Vessel Information

Fuel Analyses

Oil Analyses

Aftertreatment System(s)

Analytical Technique(s)

Data

Protocol(s) Implemented

Observations

Any Pertinent Observation not in Data

Recommendations

- Strive for National and International Input and Acceptance
- Work through Professional Societies
  - SNAME and CIMAC
- Involve Operators, Ports, Classification Societies, and Regulatory Agencies
- Propose SNAME-Sponsored Workshop as Productive Forum to Launch Effort

Summary

- Background – Need for Universal Protocols
  - Well engineered, clearly documented, widely shared
- Challenge – Creating Acceptable Protocols
  - Critical elements: end use, msmt. methodology, accuracy, repeatability, instrumentation, operating conditions, quality assurance, reporting
  - Complicating factors: fuel variation, variable control/correction, in-service operation limitations
  - Development process: wide collaboration
- Invitation – Participation Welcome!