Real World Emissions Testing
Based on FTIR Technology

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Contents

- FTIR Technology Overview
- Features and Benefits of FTIR for Automotive and PEMS use
- FTIR Accuracy and Correlation (Real World Data)
- Conclusions
What is FTIR?

Multi-component gas analyzer based on **Fourier Transform Infra-Red** technology.

Current FTIR technology allows for:

- Continuous measurement of up to 40 gases
- 5Hz data acquisition
- Fast response time ($T_{10-90} < 1.5$ sec)

**FTIR** is the ideal instrument for

- Engine development
- Aftertreatment calibration
- Catalytic converter development
Typical FTIR System Configuration (Vacuum)
Spectrometer

- The FTIR analyzer is an infrared spectrometer, configured as a dynamic multi-component gas analyzer.
- FTIR Technology uses an interferometer, infrared light source, heated gas cell (191 °C) and a cooled infrared detector.
- MKS 2030HS Spectrometer – 16 micron, one-half wave number resolution (0.5CM⁻¹), LN₂ Cooled Detector.
Michelson Interferometer creates interfering beams using:

- IR Light source
- Beam splitter
- Moving mirror
- Fixed mirror

A Helium Neon (HeNe) Laser determines mirror position, velocity and travel direction.

The output is a Interferogram, containing information about all wavenumber frequencies within the mid-infrared spectral range.
Sample Gas Cell

- Heated to 191° C
  Prevents condensation

- **5.1m Path**
  For high sensitivity

- **200 mL cell volume**
  For fast response time

5.1 meter path (32 passes)
Frequency Absorption

Each molecule has a specific Infrared frequency where it absorbs the IR radiation. (Bending, stretching, twisting, vibrating, etc. the molecule)

Because of the constructive (and destructive) interfering beams, the detector can read information about every wavelength in the infrared range simultaneously.

The interfering beams travel through the sample gas, where some energy is absorbed by gas molecules and some is transmitted to the detector.

The transmitted portion (not absorbed) reaches the detector.

The absorbed portion does not reach the detector, and is directly proportional to the amount of gas molecules in the sample.
Interferogram to Gas Concentration

Signal as a function of time (Position of Moving Mirror)

Signal as a function of frequency, (with reference)

Fourier Transform algorithm

\[ I(\tilde{\nu}) = \int I(x)D(\tilde{\nu})e^{2\pi i x \tilde{\nu}} \, dx \]

Remove Background

\[ A = -\log(I/I_0) \]

Spectrum Analysis

- Method Determination (Gas, Diesel, CNG, Etc.)
- Analysis of absorption regions
- Speciation of gases
Conditioning Unit

- **Communication and Control**  Spectrometer, PC, heated line & filter

- **Gas Handling**
  Zero and span gas regulation and distribution, for calibrations, purging and background

- **Cell Pressure Control**
  Controls the spectrometer cell pressure

- **Sample Conditioning**
  Cools sample and removes water (after spectrometer, prior to pump and mass flow meter)

- **Power Conditioning**
  Distributes power to spectrometer, HL, HF, and PC; accepts AC or DC (on-board only) input
Cell Pressure Sampling

**Vacuum Pressure**

- Vacuum controlled cell
- Faster time response ($T_{10}-T_{90} \sim 1.5$ sec)
- Decreased consumption of exhaust gas

**Atmospheric Pressure**

- Allows for the availability of standard calibration libraries, methods and hundreds of gases/ranges
- Allows for easy integration, of systems already operating at atmospheric pressure
Vacuum Pressure Sampling

Vacuum pressure advantages:
Less gas degradation, decreased exhaust gas consumption, and significant reduction in the response time.
Sampling Rate

The FTIR spectrometer can sample at selectable rates, up to 5 Hz.

5 Hz sampling rates provide superior transient sampling, capturing more data fluctuations than 1 Hz.
Messbare Gase

- Misst alle Gase die im mittleren Infrarot Spektrum absorbieren
- Messung aller regulierten Gases ausser THC*
- Mehrere konfigurierbare Messbereiche (z.B. CO\textsubscript{Low} and CO\textsubscript{High}).
- Investitionssicherung - Erlaubt Messungen von Gasen, die in der Zukunft von Interesse sein könnten.

*THC is calculated (sum of HC’s) and based upon a FID correlation factor
Evaluation by Regulatory Agencies

40 CFR Part 1065

System Response
40 CFR §1065.308

Linearity Verification
40 CFR §1065.307

Accuracy, Repeatability, Noise
40 CFR §1065.305

Interference Verification
40 CFR §1065.375

Meets or exceeds US EPA and Euro Reg 49 verification requirements
(for regulated gases)
FTIR Customer Value

Factory calibration remains stable during life of the FTIR
No requirement for daily gas calibrations

Measures up to 40 Gases
Replaces multiple conventional analyzers

Raw data files can be reprocessed with a modified gas analysis method. No need to repeat the test

Requires almost no maintenance, because of it’s simple design
Much more reliable, compared to conventional analyzers

Only one physical analyzer simplifies the whole system
Only one delay time for dynamic analysis

No requirement for daily gas calibrations or Linearizations
Customer Benefits

- **Secure Investment**
  Gases that might be of interest in the future can be added without the need to integrate additional analyzers.

- **Low Total Cost of Ownership**
  Up to 40% lower operating cost compared to conventional analyzer systems due to less:
  - Maintenance
  - Operational work load (calibrations, diagnostics)
  - Required training
  - Span gas requirements

- **High Level of Flexibility**
  Can be utilized for many different applications and easily be moved between different test locations.

- **Excellent Correlation**
  With conventional gas analyzer systems.
Benefits of FTIR - One Instrument

- Replaces NDIR
- Does Not Require CVS / Dilute
- Replaces NDUV / CLD
- Does Not Require Dry to Wet Conversion
- Replaces GC Instruments
- Does Not Require Time Align Gas Instruments
- Replaces Impinger Systems
- Does Not Require Daily Calibrations
- Replaces Cutter FID
- Does Not Require Linearization
- Replaces Laser Diode or QCL
- Does Not Require Drift Correction
Correlation with Conventional Analyzers

Our testing shows FTIR correlation is Approx. ±2%, when comparing to conventional analyzers (NO, NO₂, CO, CO₂, CH₄)
Typical Applications (On-Board)

- Testing under Real-World Driving conditions
- Testing in harsh environments and high altitude
- Catalyst Development
- Evaluation of fuel additives without the need for a chassis dynamometer
- Correlation between test cell and real-world test results
- Emissions modeling in actual vehicle operational locations
PEMS FTIR Application

**Problem**
- AC power availability
- Road vibration
- Pressure changes (altitude)
- Weather conditions
- Battery charge level

**Solution**
- DC power inlet (24V)
- Vibration dampening system
- Pressure control system
- Environment control box
- Charge indicator with alarm
On-Board Vibration Dampening

No deflection on the gas concentration, during G-Force deflections from major road vibration
Typical FTIR PEMS Components

GPS Acquisition Unit and Software
Allows for GPS data (latitude, longitude altitude and speed), to be recorded and time-aligned with the emissions data.

ECU Acquisition Unit and Software
Allows for the vehicle ECU data to be recorded and time-aligned with the emissions data.

Video Camera Monitoring System and Software
Allows for live on-road video recording, time aligned with emissions data, GPS and ECU vehicle data.
PEMS FTIR In-Use

Hong Kong EPD On-Road Testing

- **Coach Vehicle**
  - Tsing Yi – Stop & Go
  - 7.14L Diesel
  - 12-DEC-2012

- **Double Decker Bus**
  - Kowloon – Urban
  - 10.8L Diesel
  - 08-JAN-2013

“One of the most dense streets in the world”
In-Use Hong Kong EPD Coach

Gaseous Measurement
A&D BOB-1000FT and Sensors SEMTECH-DS

HK-EPD Defendable Data Methods

- SEMTECH-DS: 1065 verification tests current
- 1065 In-use recommendations (e.g. drift corrections, etc.)
- Linearity Verification, Span (pre and post) and 3-hr Audit’s
Hong Kong EPD Coach – NO$_x$ Data

FTIR Readings Slightly Larger
- 5Hz (FTIR) vs 1Hz (DS) higher transient peaks
- NDUV Chiller Loss (5% allowed per 1065.376)

*SEMTECH-DS wet (Calculated)*
Hong Kong EPD Coach - NO$_x$ Data

**NO$_x$ Mass Accumulation**

1.16 %

![Graph showing NO$_x$ Mass Accumulation](image_url)
Hong Kong EPD Coach – CO₂ Data
Hong Kong EPD Coach – CO₂ Data

CO₂ Mass Accumulation

2.50 %

FTIR CO₂
DS CO₂

(Grain)

(Sec)
Hong Kong EPD Coach – CO Data

CO peaks generally agree but FTIR peaks are larger

Reasons:

- 5Hz (FTIR) vs 1Hz (DS)
  (higher transient peaks)
- FTIR high Range @ 4% CO
- Peaks significantly above NDIR-DS Span Calibration Value (200 ppm)
Hong Kong EPD Coach – CO Data

- At low concentrations CO follows same trend
- FTIR readings approximately ~50-75ppm lower
- Detection limit of DS-NDIR ~ 50ppm
Amonia (NH₃) Slip

FTIR can detect NH₃ slip (SCR) when exhaust temperature drops
Hong Kong EPD Chassis Dynamometer Test Bed

Dilution Tunnel

Heat Exch.

CVS

BOB-1000FT

SEMTECH-DS

ECOSTAR
Cold Start Test 1

CO₂ Test 1

<table>
<thead>
<tr>
<th>Model</th>
<th>ECOSTAR</th>
<th>SEMTECH-DS</th>
<th>BOB-1000FT</th>
<th>CVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions (g/24m)</td>
<td>275.00</td>
<td>250.00</td>
<td>150.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Bar graph showing emissions for different models.
Warm Start Test 2

![CO₂ Test 2 Graph]

The graph compares CO₂ emissions for different tests: ECOSTAR, SEMTECH-DS, BOB-3000FT, and CVS. The y-axis represents grams per kilometer, ranging from 0.00 to 300.00 grams per kilometer. The x-axis lists the different tests. Each bar indicates the average emission level with error bars showing variability.
Cold Start Test 1

CO Test 1

Graph showing CO emissions for different fuel types:
- ECOSTAR
- SEMTECH-DS
- BOE-1000FT
- CVS
Warm Start Test 2

CO Test 1

- ECOSTAR
- SEMTECH-DS
- BCB-1000FT
- CVS

Values are measured in Grams per Kilometer (G/km).
Cold Start Test 1

After evaluation, Hong Kong EPD determined an issue with the contractors CVS/CLD system.

Hong Kong EPD is on record stating that they believe the PEMS NOX is accurate, not the CVS NOX (≈ +20%)
Warm Start Test 2

After evaluation, Hong Kong EPD determined an issue with the contractors CVS/CLD system.

Hong Kong EPD is on record stating that they believe the PEMS NOX is accurate, not the CVS NOX (~ + 20%)
Climbing Mount Fuji
Road Test On Mt. Fuji

**FTIR 25 Gas Graph**
Mount Fuji Cylinder Gas

Stable concentrations have been verified up to 3,200m (11,000 feet)
Conclusion

- FTIR Technology is a highly accurate method for exhaust gas measurement

- FTIR technology has many advantages over traditional PEMS and conventional analyzers

- FTIR has good correlation to conventional analyzers, for regulated components, while also measuring all gases of interest – with one analyzer

- FTIR as a PEMS instrument will become increasingly important, as we continue to monitor and research additional gases, and more exotic gasses
Vielen Dank!