design considerations for brake emissions measurements using inertia dynamometer testing

45th PMP Meeting, 07-08 Nov 2017

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why?
it is a journey...
learning + collaboration + harmonization
“If a test is not repeatable, it is only an anecdote”

Nature – International weekly journal of science
challenge 1 – continuous data recording

LACT

WLTP

ISO 26867
challenge 2 – variability

Sachse, H. et al. TU Ilmenau
Challenge 2 – variability

Figure 2: Estimate of the reasons for the divergence between type-approval and real-world CO₂ emission levels for new passenger cars in the past as well as in the future, with and without introduction of the WLTP (for details, see Stewart, Hope-Morley, Mock, & Tietge, 2015).

Source: ICCT- From Lab To Road – 2015 Update
challenge 3 – air handling

\[ W = V \]

\[ \eta \text{ gravitational settling} \]
\[ \eta \text{ diffusional deposition} \]
\[ \eta \text{ turbuphoretic} \]
\[ \eta \text{ constrictions} \]
\[ \eta \text{ bends} \]
\[ \eta \text{ aspiration} \]
\[ \eta \text{ thermophoretic} \]
\[ \text{polydisperse coagulation} \]
\[ \text{resuspension} \]
\[ \text{etc, etc,} \]
Various initial concentrations. The concentration remains almost constant at low initial concentrations ($<10^7$ p/cm$^3$) but it may reduce significantly at higher concentrations.
how
questions

1. emission’s metrics, indexes
2. size ranges
3. measurement principles
questions
1. emission’s metrics, indexes
2. size range
3. measurement principles

potential WPs
1. air handling, losses, isokinetics
2. minimum specs for PMS
3. calibration, uncertainty, sign-off
testing environment

- toxicology & V2R
- commercial vehicles
- regulation & rulemaking

- open data
- sync with other SDOs
- brake, dyno, PMS agnostic

Example:
- ISO 9096
- ISO 14956
- PMP WLTP-B
- EPA M1 & M1A
- ISO 17025
- ISO 16911-2
- ISO 3966
- ISO 5725
- ISO 12141
- ISO 9169
- ISO 8756

Examples only
what
LINK’s approach

available as upgrade to current dyno designs
ruggedness (data fusion, 8d/2d/isok/round duct)
r&R (fixture, environmental, duct finish)
ducting layout - A (150-mm duct)
ducting layout - B (150-mm duct)
ducting layout - C (150-mm duct)
<table>
<thead>
<tr>
<th>feature</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>8d/2d, isokinetics, electropolish</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>floorspace</td>
<td>+</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>instrument layout for isokinetics</td>
<td>++</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>simplicity and installation</td>
<td>+++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>duct transport efficiency</td>
<td>+++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>ruggedness to airflow/duct size</td>
<td>+++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>low leaks and ease of cleaning</td>
<td>+++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>short distance to Pitot tube</td>
<td>+++</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>
brake fixtures

**DO**
post or universal

- minimal interruption to airflow
- allows smaller (round) brake enclosure
- predictable interface with seals

**DON’T**
knuckle or L1

- unpredictable turbulence around the brake
- large variability in knuckle size and geometry
- significant variation at seal interface
Envelope dimensions for disc brake fixtures ~ ECE M1/N1

- Caliper plate: 200-230 mm
- Rotor driver
- Universal fixture: 160-250 mm
- Diameter: Ø 275-430 mm
ISO 3:1973 - R5 series for agnostic sizes and airflows

<table>
<thead>
<tr>
<th>Sampling line flow, l/min</th>
<th>1.0</th>
<th>1.5</th>
<th>2.5</th>
<th>4.0</th>
<th>6.0</th>
<th>10</th>
<th>15</th>
<th>25</th>
<th>40</th>
<th>60</th>
<th>100</th>
<th>150</th>
<th>250</th>
<th>400</th>
<th>600</th>
<th>1000</th>
<th>1500</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct diameter, mm</td>
<td>1.0</td>
<td>1.5</td>
<td>2.5</td>
<td>4.0</td>
<td>6.0</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td>40</td>
<td>60</td>
<td>100</td>
<td>150</td>
<td>250</td>
<td>400</td>
<td>600</td>
<td>1000</td>
<td>1500</td>
<td>2500</td>
</tr>
<tr>
<td>Airflow from brake enclosure, m³/h</td>
<td>1.0</td>
<td>1.5</td>
<td>2.5</td>
<td>4.0</td>
<td>6.0</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td>40</td>
<td>60</td>
<td>100</td>
<td>150</td>
<td>250</td>
<td>400</td>
<td>600</td>
<td>1000</td>
<td>1500</td>
<td>2500</td>
</tr>
</tbody>
</table>
isokinetic nozzle size = \( f \) (gas airflow, sampling line flow)
Particle Measurement System – PMS

EEPS & CPC, 11 l/min
5.6-560 nm
1-to-10,000 #/cm³

QCM M140
10 l/min
Isokinetic sampling

APS
6 l/min

0.045-2.5 µm

0.37-20 µm
RH conditioner and 6-stage QCM impactor

RH conditioner ensures collection at medium RH range (~60-65 %)

vacuum pump with precise orifice to control the flow rate
transport losses and sampling line efficiency

<table>
<thead>
<tr>
<th>design</th>
<th>approval</th>
<th>testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>STP conditions</td>
<td>STP conditions</td>
<td>actual T, RH, Q</td>
</tr>
<tr>
<td>Q (min, max)</td>
<td>(T, RH) ± limits</td>
<td>actual sampling train</td>
</tr>
<tr>
<td>isokinetics</td>
<td>Q (min, max)</td>
<td>actual background</td>
</tr>
<tr>
<td></td>
<td>coagulations</td>
<td>coagulation per test</td>
</tr>
<tr>
<td></td>
<td>reference brakes</td>
<td>periodic spot-checks</td>
</tr>
</tbody>
</table>
transport efficiencies - (100-250 mm duct, 250-2500 m³/h)
transport efficiencies - (150-250 mm duct, 250-1000 m³/h)
Aerosol Calculator
by Paul Baron, expanded by Link Engineering Co.
For comment and feedback: pbaron@cdc.gov

This program is freeware
The program is free of charge for individual use, but the author requests that it not be sold or used commercially without written consent of the author.

Note: Some calculations require that the Iteration option be turned on (e.g., use 100 iterations):
Change under Tools menu/Preferences (or Options)/Calculation (check help menu if not found in this location)

Many equations from Willeke and Baron (W&B), Aerosol Measurement, Van Nostrand Reinhold 1993,
from Baron and Willeke (B&W) Aerosol Measurement, 2nd Edition, J Wiley and Sons, 2001,
Hinds equations from 1st and 2nd edition are same except as noted

Duct airflow
400 m^3/h

Duct diameter
0.25 m

Particle velocity in duct - Uo
2.3 m/s

Sampling flow
10 l/min

Nozzle diameter
7.5 mm

Particle velocity in nozzle - U
3.8 m/s

Particle density
2500 kg/m^3

Particle Reynolds Number (B&W 4-1; W&B 3-1; Hinds 2-41)

Temperature
293.15 Kelvin

Pressure
101.3 kPa

Particle diameter
0.0056 to 18 µm

Particle velocity
2.3 m/s

Air density = 1.204785775 kg/m^3

Air viscosity = 1.80711E-05 Pa*s

Reynolds number (Re) = 0.000845086 to 2.716347647

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<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>Dynamometer operating parameters and controls</td>
<td>(R): required; (D): desired</td>
<td></td>
</tr>
<tr>
<td>1.1.</td>
<td>Data export</td>
<td>(R): 10 Hz in-stop, 1 Hz off-brake</td>
<td>This will allow the proper sync with the TSI data</td>
</tr>
<tr>
<td>1.2.</td>
<td>Data exchange</td>
<td>(R): compatible</td>
<td>With different protocols from brake emissions measurement systems and vendors: TBD</td>
</tr>
<tr>
<td>1.3.</td>
<td>Cycle controls for speed profiles (WLTP)</td>
<td>(R): TrackSim</td>
<td>Required to follow the speed line of the cycle. Ensure data export</td>
</tr>
<tr>
<td>2.</td>
<td>Sampling, isokinetics, brake enclosure, and air handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.</td>
<td>Airflow measurement</td>
<td>(R): provide total airflow per ISO stds regarding position and average</td>
<td>Per ISO 9096 and related stds. Define with Lab points for manual measurement of air speeds</td>
</tr>
<tr>
<td>2.2.</td>
<td>Air supply</td>
<td>(R): ability to connect to the main air handling system of the dyno</td>
<td></td>
</tr>
<tr>
<td>2.3.</td>
<td>Ability to handle and measure total airflow</td>
<td>(R): (250 to 600) m³/h (D): (250 to 1500) m³/h</td>
<td>fixed during test; adjustable between tests</td>
</tr>
<tr>
<td>2.4.</td>
<td>Incoming air filter</td>
<td>(R): HEPA 13 (D): HEPA 14 or &gt; ULPA 15</td>
<td>Assess need to have a stack of multiple filters on incoming and outlet air</td>
</tr>
<tr>
<td>2.5.</td>
<td>Activated carbon filters</td>
<td>Included on filtering stacks</td>
<td></td>
</tr>
<tr>
<td>2.6.</td>
<td>Background (blank) emissions</td>
<td>(R): 5 times below test collection</td>
<td>ISO 9096</td>
</tr>
<tr>
<td>2.7.</td>
<td>Vacuum sealing inside sampling train</td>
<td>(R): The flow rate &lt; 2% of the normal flow rate at the max vacuum</td>
<td>Applies to sampling train under vacuum with all nozzles sealed/blocked</td>
</tr>
<tr>
<td>2.8.</td>
<td>Environmental conditioning</td>
<td>(R): room air with basic temp control (D): (20 ± 5)°C, (50 ± 10)%RH</td>
<td></td>
</tr>
<tr>
<td>2.9.</td>
<td>Straight length before the aerosol sampling position from last (nearest) upstream duct disturbance</td>
<td>(R): 8 diameters (D): 10 diameters</td>
<td>Per EPA Method 1 &amp; 1a. also applies to air speed</td>
</tr>
<tr>
<td>2.10.</td>
<td>Straight length after aerosol sampling position from next (nearest) downstream duct disturbance</td>
<td>(R): &gt; 2 diameters</td>
<td>Per EPA Method 1 &amp; 1a. also applies to air speed</td>
</tr>
<tr>
<td>Item</td>
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<td>Comments</td>
</tr>
<tr>
<td>------</td>
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</tr>
<tr>
<td>2.11.</td>
<td>Duct size and geometry</td>
<td>(R): keep the same</td>
<td>Applies to wet area after the brake enclosure</td>
</tr>
<tr>
<td>2.12.</td>
<td>Duct bends</td>
<td>(R): Ro 4-to-6</td>
<td>Ro = Curvature ratio = bend radius/duct radius. Applies on wet area and sampling train</td>
</tr>
<tr>
<td>2.13.</td>
<td>Transition angles in wet areas</td>
<td>(R): &lt; 30° enclosed angle</td>
<td>Applicable to enclosure outlet constriction</td>
</tr>
<tr>
<td>2.14.</td>
<td>Isokinetic sampling</td>
<td>(R): within 10% of the theoretical isokinetics flowrate</td>
<td>See ISO 9096</td>
</tr>
<tr>
<td>2.15.</td>
<td>Wet area ducting and sampling train material</td>
<td>(R): stainless steel</td>
<td>Ensure smooth and ease of cleaning if needed</td>
</tr>
<tr>
<td>2.16.</td>
<td>Enclosure design and shape</td>
<td>(R): round to accommodate M1/N1 brake sizes indicated in Figure 2</td>
<td>Fixture with rotor near the center on the enclosure opening in the axial direction</td>
</tr>
<tr>
<td>2.17.</td>
<td>Figure 2: brake fixture envelope dimensions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. **Real-time emission measurement system**

<table>
<thead>
<tr>
<th>Item</th>
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<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.</td>
<td>Dynamic range for real-time measurement</td>
<td>(R): 23 nm to 10 µm</td>
<td>Gravimetric sampling highly desirable</td>
</tr>
<tr>
<td>3.2.</td>
<td>Data format</td>
<td>(R): Ability to export analog data via standard protocol</td>
<td>Specify protocol and connectors See AK Protocol</td>
</tr>
<tr>
<td>3.3.</td>
<td>Data exchange</td>
<td>(R): Data sync for basic controls, alarms, and status messages</td>
<td>Coordinate details with PMS vendor</td>
</tr>
</tbody>
</table>

4. **System validation**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Value / parameter</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.</td>
<td>Results compared to reference brakes and friction couples (A, B, C)</td>
<td>(R): within XX °C thermal regime (R): within X% of emissions metrics</td>
<td>Temperature and emission targets will be a function of the reference brake used</td>
</tr>
</tbody>
</table>
special acknowledgments

Troy Caldwell & Terry StAubin
Andrea Tiwari & Bob Anderson