FUEL CONSUMPTION MEASUREMENT UNCERTAINTY

How can I evaluate the quality of my measurement results?

Romain Lardet
AVL List GmbH

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1. What do we mean by Measurement Uncertainty?

2. Example of measurement uncertainty evaluation based on actual steady-state measurements

3. Sources of Measurement Uncertainty

4. Evaluating the measurement uncertainty in your testfield

5. AVL Measurement Quality Program (MQP)
MEASUREMENT UNCERTAINTY : THE BASICS

- “uncertainty of measurement” means:
  Doubt about the validity of the result of a measurement

- According to the GUM* there are 2 main ways of evaluating the measurement uncertainty:
  
  TYPE A : method of evaluation of uncertainty by the statistical analysis of series of observations
  = evaluation based on actual measurements

  TYPE B : method of evaluation of uncertainty by means other than the statistical analysis of series of observations
  = evaluation based on estimating what the different sources of uncertainties are = modelling of the stochastic (random) and systematic effects on the measurement.

* GUM = Guide to the expression of uncertainty in measurements edited by the Joint Committee for Guides in Metrology (JCGM – Working Group 1)
EVALUATION BASED ON ACTUAL MEASUREMENTS (TYPE A)

some mathematics are necessary:

• Mean of N observations (measurements) of the quantity q

\[ \bar{q} = \frac{1}{n} \sum_{k=1}^{n} q_k \]

• Standard Deviation of N observations of the quantity q

\[ s^2(q_k) = \frac{1}{n-1} \sum_{j=1}^{n} (q_j - \bar{q})^2 \]

• Best Estimate of the Variance of the Mean = Standard Uncertainty U

\[ U = \sqrt{\frac{s^2(q_k)}{n}} \]
EVALUATION BASED ON ACTUAL MEASUREMENTS (TYPE A)

...and some more:

- Expanded Measurement Uncertainty (incl. coverage factor @95%)

\[ U_{95,n} = t_{95,n} \cdot \sqrt{\frac{s^2(q_k)}{n}} \]

Where \( t \) is the student factor @95% defined in the table below.

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<th>Degrees of freedom</th>
<th>Fraction ( \alpha ) in percent</th>
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It is usual to express measurement uncertainty of type A as an expanded measurement uncertainty with a coverage factor of 95% as described in the formula above.
MEASUREMENT UNCERTAINTIES EVALUATED BY THE AVL FUEL MEASUREMENT DEVICES

Expanded Measurement Uncertainty $U_{95,6}$ for 6 measurements of 5 seconds

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EXAMPLE OF MEASUREMENT UNCERTAINTY EVALUATION BASED ON ACTUAL STEADY-STATE MEASUREMENTS.

Hypothesis:
- Engine Speed / Torque / T_oil / T_water are stable.

Procedure:
- repeat N=6 steady-state averaged measurements of t = 10 seconds (e.g.: with a data rate 5 Hz, this is 10*5 = 50 samples repeated 6 times)
- calculate the standard deviation S of those 6 averaged measurements
- calculate the expanded measurement uncertainty @95% for 6 measurements (the student factor t95,n=6 = 2.45) using the formula provided before.

Example here on the 6 first values:
U_{95,6} = 0.2 g/kWh (0.1% of the average of the 6 BSFC measurements)

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WHAT IS A “GOOD ENOUGH” MEASUREMENT UNCERTAINTY THEN?
EXAMPLE WITH MODELLING BASED ON DOE

- With DOE the testbed effort can be reduced by up to 90% (typ. 60%)
- Prerequisite to gain the benefit are repeatable measurement results = low measurement uncertainty
- in this example, to generate the required DOE model with a certain confidence level, 10 times more measurement points are required if the repeatability is +/- 3,5g/kWh instead of +/- 1g/kWh

an uncertainty @95% around ~ 1 g/kWh or less is usually required for efficient testing

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EVALUATION OF TYPE A : PROS & CONS

PROS

• easy to setup and automate with a running engine
• gives a good estimation of the repeatability one can obtain in given conditions at a given operating point.
• can be easily combined with the measurement of Speed / Torque in order to check the uncertainty of the specific fuel consumption measurements

CONS

• can not evaluate the systematic uncertainty due to a wrongly calibrated or drifting sensor (this effect is “hidden” in the measurement).
• if the engine is not perfectly stable, this instability will be included in the calculated measurement uncertainty. it is not always possible to distinguish between the engine “uncertainty” and the uncertainty of the fuel system + installation.

The systematic uncertainty will impact especially the comparison of measurements with other methods (e.g Carbon Balance) or the reproducibility when performing the same measurements on the same engine but in another testcell with a different fuel system.
Sources of Systematic Uncertainties

- e.g.: 0.1% of measured value @95% CI for an AVL FuelExact Mass Flow Sensor, incl. the systematic measurement uncertainty of the calibration testbed itself.
- Don’t forget the other systematic uncertainties: non-linearities between calibration points, Drift, temperature influence...etc. Those can be significant!
- AVL calibrates the sensors (Coriolis or PLU) with fuel like medium
- AVL calibration laboratory has 1 main testbed accredited ISO17025 and 1 who will receive accreditation in Q2 / 2015

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STOCHASTIC UNCERTAINTIES = ALL OTHER EFFECTS THAT CAN NOT BE COMPENSATED IN CALIBRATION

The Engine is also a stochastic source of uncertainty as it is never 100% stable. The repeatability of the speed / torque control impacts as well the measurement uncertainty of the BSFC.

Those effects have the following properties:

- Usually, the lower the measured flow rate, the higher is their relative impact.
- They can be specific to the sensor technology (e.g.: sensor “natural” noise).
- Contrary to popular belief, they can not always be compensated by extending the measurement time.
- They are usually minimized by optimizing the fuel system and respecting best practices of installation.

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IMPACT OF THE TEMPERATURE STABILITY ON FUEL CONSUMPTION MEASUREMENTS

Relative Errors in Fuel Consumption Measurement for different temperature gradient in °/min

Calculation based on a typical testbed setup:
2 liters of fuel between the sensor and the injectors

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TRADE OFF BETWEEN MEASUREMENT TIME, TEMPERATURE STABILITY AND FLOW RATE ACTUAL MEASUREMENTS ON A DIESEL ENGINE

Numbers based on: 1,9 l turbo common rail diesel engine; operating point: 2000 rpm / BMEP = 4 bar; 430 measurement points.

Higher measurement uncertainty caused by worse temperature stability can be partly compensated by a much higher measurement time but it increases your costs.

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INFLUENCING PARAMETERS: ELASTICITY EFFECTS

Elasticity Effects

General elasticity effects:

- flexible and mellow hoses
- membrane of pressure regulator
- Air in tubes that are filled with fuel (especially pressure sensors !)
- two-phase flow (liquid/gas) depending on pressure

Sensor ------- Fuel Volume ------- Engine

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EFFECTS OF A SMALL AMOUNT OF AIR BUBBLES ON THE REPEATABILITY OF THE MEASURED FUEL CONSUMPTION

Fuel Flow, air in the system

Fuel Flow, no air in the system

Standard deviation depending on measurement time

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ZERO CONSUMPTION VARIATION DUE TO AIR BUBBLES - A SIMPLE TEST

Comparison of online zero consumption value with and without air in the fuel application (Test 1 vs. Test 3)

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LIMITATIONS OF THE TYPE B EVALUATION (MODELLING OF UNCERTAINTIES)

- Modelling of uncertainties can lead to **underestimating** the real uncertainty because of the multiple effects. **Piping between the fuel system and the engine is a major contributor to uncertainty.**

- At low consumption (engine part-load), the main influences on uncertainty of the fuel measurement is:
  - Temperature stability of the fuel
  - Fuel volume between sensor and injectors (any model showing small volume like 300 ml of fuel is WRONG!)
  - Air trap on the engine side (engine fuel filter?)
  - Air trap in the installation between sensor and injectors (can not be modelled easily)
  - Flexible volumes
  - The instability of the engine conditioning & control (SPEED, LOAD, T_WATER, T_OIL... etc)

- AVL recommends to measure the uncertainty in the field using a reference system

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HOW CAN I EVALUATE PRACTICALLY THE MEASUREMENT UNCERTAINTY IN MY TESTFIELD?
EVALUATING THE MEASUREMENT UNCERTAINTIES WITH THE SYSTEM CALIBRATION

„System Calibration“

- **PROS**: Same environmental influences as during measurements
- **PROS**: complete calibration of the fuel system + installation (not only the sensor !)
- **PROS**: all measurement influences are taken into account:
  - systematic uncertainties
  - stochastic uncertainties: temperature effect, storage effect in pressure regulators and elasticities (e.g.: flexible hoses…) etc
- The evaluation of engine instability can not be covered though

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EXAMPLE OF SETUP AT THE TESTBED

Fuel Supply

FUEL SYSTEM

Cooling water

RS232, TCP/IP or TTL/OC

Fuel Line to engine

Fuel Consumption: Defined mass flow in Calibration procedure

Fuel Line from engine

By-pass

PC: Software

Ethnic

AVL Fuel Reference

Fuel Supply

Fuel Return

Fuel Supply

Engine

Interface connection

Hydraulic connection

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EXAMPLE: EVALUATION OF DIFFERENT FUEL SYSTEM SETUP FOR GASOLINE ENGINES WITH NO RETURN FLOW

Setup A

without fuel conditioning

Setup B

with fuel temperature and pressure control

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EXAMPLE: EVALUATION OF DIFFERENT FUEL SYSTEM SETUP FOR GASOLINE ENGINES WITH NO RETURN FLOW

![Graph showing deviation in fuel flow between Setup A and Setup B.](image)

**Setup A** and **Setup B** show the deviation in fuel flow (kg/h) across different fuel flow rates.

**PC: Software FCC**

**AVL Fuel Reference**

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ANONYMOUS POLLING:

which of this statement do you feel is more corresponding to your situation?

please write on the small piece of paper the number 1, 2 or 3 corresponding to your situation.

1. In my testfield, I always have very good comparison of FC measurements between different testcells, even at low flow rate

2. In my testfield, it is sometimes hard to compare FC measurements on the same engine in different testcells using different fuel systems, especially at low flow rate

3. I do not know the status (e.g.: because fuel consumption is not my area of expertise or other reasons)
RESULTS 44 PARTICIPANTS*

In my testfield, I always have very good comparison of FC measurements between different testcells, even at low flow rate

In my testfield, it is sometimes hard to compare FC measurements on the same engine in different testcells using different fuel systems, especially at low flow rate

I do not know the status (e.g.: because fuel consumption is not my area of expertise or other reasons)

Answer 1
Answer 2
Answer 3

*one of the answer was 1.5...
AVL MEASUREMENT QUALITY PROGRAM FOR FUEL CONSUMPTION MEASUREMENT

• **Aim:**

Assess the quality of the fuel consumption measurements for each different type of fuel system present in the testfield.

• **How:**

• Complete installation check
• System calibration with AVL Fuel Reference
• Test Run Protocol showing deviation between Fuel Reference & UUT as well as measurement uncertainty according to Type A evaluation.

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Just by looking at the deviations between the Fuel Reference and the local fuel systems we could identify very large errors, especially at low flow rate.
Main reasons for errors were:
- calibration errors, drift errors of the sensor
- poor temperature conditioning (well above +/- 0.02°C)
- non optimized installation
OTHER TEST RUN PROTOCOL (ISO)

AVL Fuel Calibration Controller

Calibration report

**General**
- Test bed: 10
- FCC software version: 3.0.1.1987

**Calibration Unit (CU)**
- Device name: AVL Fuel Reference
- Firmware version: 3.00
- Type: PLU
- Serial number: S/N0118
- Reference temperature (CU): 20.0 °C
- Sensor Manufacturer (1): PLU
- Serial number (1): 2123
- Sensor Identification (1): BW5360

**Unit Under Test**
- Device name: AVL FuelExact
- Firmware version: 3.11
- Type: FE PLU 300 FF GH0650
- Serial number: 178
- Active sensor manufacturer: PLU
- Active sensor serial number: 121 - 75/l/h
- Adjustment date: 03/12/2014

**Calibration Conditions**
- Measurement domain: Volume
- Ambient temperature: 20°C
- Fuel type: Gasoline
- Expansion coefficient: 0.0010 1/K
- Demand temp. of Conditioning Unit: 10.0 °C
- Limit density deviation: 1.000 %

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<th>Type</th>
<th>Demand meas. time [s]</th>
<th>Demand flow rate (CU) [l/h]</th>
<th>Limit flow dev.(UUT-CU) [%]</th>
<th>Repeats</th>
<th>Meas. time [s]</th>
<th>Temp. @ Flow Sensor (CU) [°C]</th>
<th>Flow rate (CU) [l/h @Ref. Temp. (CU)]</th>
<th>Flow rate (UUT) [l/h @Ref. Temp. (CU)]</th>
<th>Flow dev. (UUT-CU) [%]</th>
<th>Meas. uncertainty flow dev. [%]</th>
<th>Density @ ref. temp.(CU) [kg/m³]</th>
<th>Density dev. (UUT-CU) [%]</th>
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FUEL CONSUMPTION MEASUREMENT UNCERTAINTY HOW CAN I EVALUATE THE QUALITY OF MY MEASUREMENT RESULTS?

• Evaluating measurement uncertainty & repeatability is critical to perform efficient engine optimization.

• During engine testing, it is easily possible to evaluate the measurement uncertainty due to stochastic parameters using simple statistical analysis of repetition points (largest influences being: temperature stability, storage effect, sensor noise, engine stability).

• It is however not possible to figure out the measurement uncertainty due to systematic effects without comparing the measurement of the fuel system against a reference value. These errors can become very large using a non-optimized fuel system/installation, especially in engine part-load (=low fuel consumption!)

• AVL offers Measurement Quality Programs aimed at evaluating the overall measurement uncertainty and providing counsel on how to reach state-of-the-art measurement quality for best testing efficiency.

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attached to the presentation is the GUM and a “beginners guide to measurement uncertainty” that I found on internet.

if you have further questions or if you wish to have an assessment of your measurement uncertainty and quality in your own testfield, please do not hesitate to contact me:

Romain LARDET, AVL Graz, Austria
email: romain.lardet@avl.com
tel: +43 316 787 1935

You can also get in contact with me via your local AVL UK account manager and refer to this workshop.

Thank you for your participation and encouraging comments!

Sincerely,
Romain
THANK YOU