Physikalisch-Technische Bundesanstalt
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GUM-compliant propagation of conformity statements and maximum permissible errors

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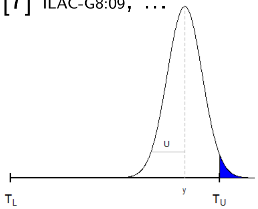
Conformity assessment

- decide whether an item conforms to requirements (tolerance intervals)
- according to [9] ISO 17025, [13] OIML G 19, [17] WELMEC 4.2, [7] ILAC-G8:09, ...

Conformity statements

- risk-based, account for uncertainty [9]
- minimum information [9]
  - which specifications are (not) met
  - the decision rule applied



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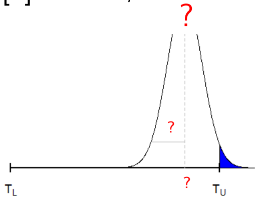
⇒ often unavailable: measured value, uncertainty (or distribution)



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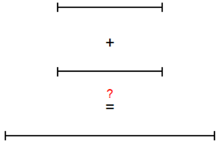
Conformity statements



- risk-based, account for uncertainty [9]
- minimum information [9]
  - which specifications are (not) met
  - the decision rule applied

$\Rightarrow$ often unavailable: measured value, uncertainty (or distribution)

Question: Can we reuse conformity statements to disseminate traceability?

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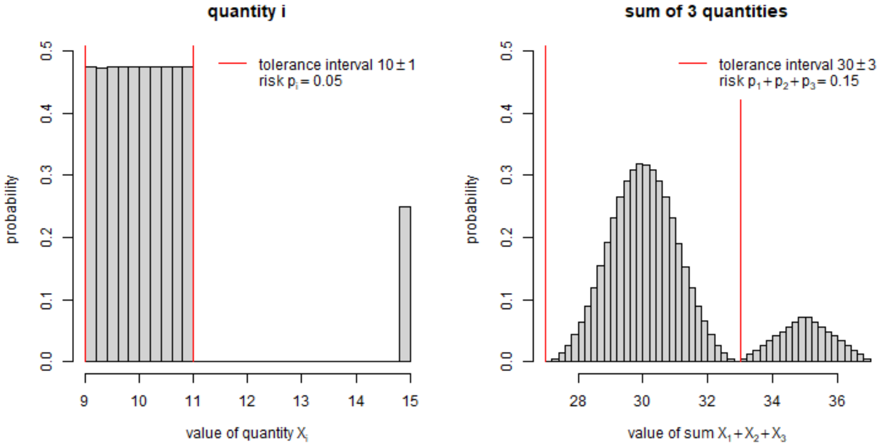

$\Rightarrow$ risks of non-conformance may accumulate

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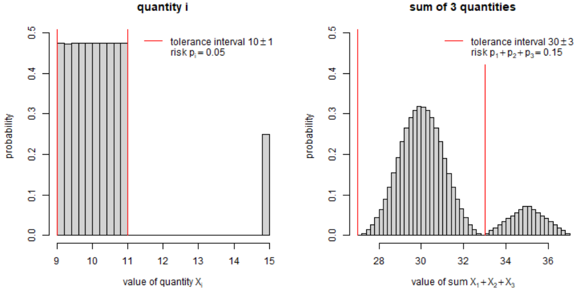

Lemma

Let $P\left(Y_i \notin y_i \pm MPE_i\right) = p_i$ *and* $c_i \neq 0$ *for* $i = 1, 2, \ldots$. *Then the risk* $P\left(\sum c_i Y_i \notin \sum c_i y_i \pm \sum |c_i| MPE_i\right) \leqslant \min\left(\sum p_i, 1\right)$ *and equality may hold.*

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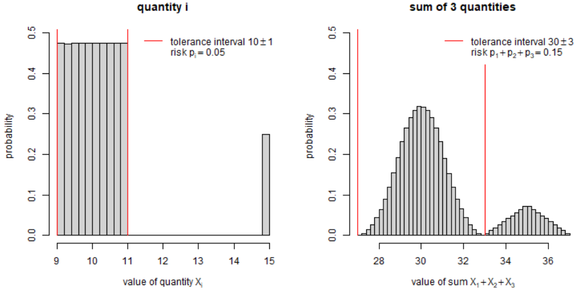

- knowledge only on conformity for each input is insufficient to judge conformity of a combination of these inputs

  also not compliant with [9], but applied in practice [15, 4]

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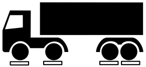
Conformity statements needed

- for the linear combination of quantities for which in turn conformity statements are available
- which comply with [9] and [3] JCGM 106: account for risk and uncertainty
- in legal metrology: to correct [15]
  e.g. long vehicle weighing, tara weighing in zero waste shops, . . .
  source: de.m.wikipedia.org/wiki/Datei:LKW_mit_Aufleger_aus_Zusatzzeichen_1048-14.svg



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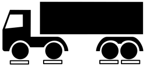

Content

- brief review of available guidance [1, 2, 3]
- develop simple, risk-based decision rules
  based on specifications and decision rule or risk for each input
- illustrate by example

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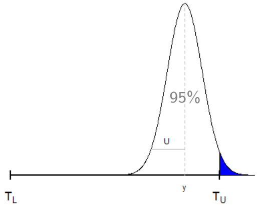
Conformity guidance in [3]: measurand expressed by

- probability density function (pdf), or
- estimate, coverage interval and probability

Guidance in [2] JCGM 101 on output pdf based on



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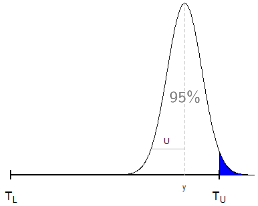

Guidance in [2] JCGM 101 on output pdf based on

- pdf for inputs
- MC method

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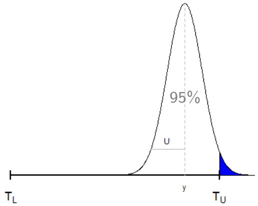

Conformity guidance in [3]: measurand expressed by

- probability density function (pdf), or
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Guidance in [2] JCGM 101 on output pdf based on

- pdf for inputs $\Rightarrow$ case by case evaluation
- MC method $\Rightarrow$ not widespread at end of traceability chain [14]

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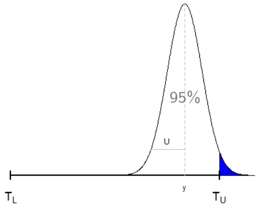

Guidance in [1] JCGM 100 on output pdf based on

- estimate, uncertainty and degrees of freedom for inputs
- Normal or t-distribution for output:
  verify CLT assumptions or Normality and independence of inputs
- apply LPU, calculate coverage factor

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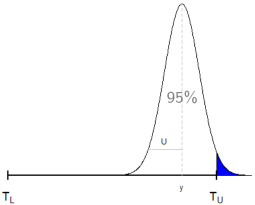

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$\Rightarrow$ available for conformity statements based on calibr. certificates [8, 5]

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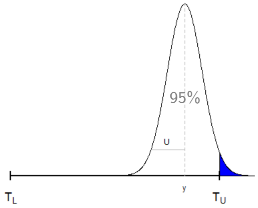

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- Normal or t-distribution for output:
  verify CLT assumptions or Normality and independence of inputs
- apply LPU, calculate coverage factor

$\Rightarrow$ available for conformity statements based on calibr. certificates [8, 5]

$\Rightarrow$ methods needed for conformity statements with less info

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Theorem (Sum of Normal and Uniform Distributions)

Let $U_i \sim U(-MPE_i, MPE_i)$ *and* $X_i \sim N(0, (MPE_i/m)^2)$ *be independent with* $i = 1, \ldots, n,\ \ m > 1.$ *Then calculation of the quantile* $-\sum MPE_i$ *of their sum* $\sum_{i=1}^{n} (U_i + X_i)$ *reduces to an essentially 1-dim. numerical integration*

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Decision Rule I: The Basis

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Let $U_i \sim U(-MPE_i, MPE_i)$ and $X_i \sim N(0, (MPE_i/m)^2)$ be independent with $i = 1, \ldots, n,\ m > 1.$ Then calculation of the quantile $-\sum MPE_i$ of their sum $\sum_{i=1}^{n}(U_i + X_i)$ reduces to the essentially 1-dim. numerical integration

$$P\left(\bar{U} + \bar{X} < -MPE\right) = \int_{-MPE}^{MPE} f_{\bar{U}}(v)\Phi\left(\frac{-m(v + MPE)}{\sqrt{\sum MPE_i^2}}\right) dv\ .$$

with MPE $= \sum$ MPE$_i$ and Φ the standard Normal CDF

- as $\bar{U} = \sum_{i=1}^{n} U_i$ and $\bar{X} = \sum_{i=1}^{m} X_i$ analytic
  for non-id. distributed U_i: generalization of Irwin-Hall distribution [16]

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Decision rule I assumes:

- measurements for each input Y_i conform to specification $\pm\mathrm{MPE}_i$
- conformity was established by an instrument
  with $X_i \sim N(0, u_i^2)$ and $u_i \leqslant \mathrm{MPE}_i/m$ (for $m > 1$)
- $Y_i = X_i + U_i$ for each $i = 1, \ldots, n$
- independence of all quantities involved

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Decision rule I assumes:

- measurements for each input Y_i conform to specification $\pm\mathrm{MPE}_i$
  $\Rightarrow U_i \sim u^{(i)} + U(-\mathrm{MPE}_i, \mathrm{MPE}_i)$ cf. [1, 2]
- conformity was established by an instrument
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- $Y_i = X_i + U_i$ for each $i = 1, \ldots, n$
- independence of all quantities involved

$\Rightarrow$ apply Theorem to calculate risk of $\sum c_i Y_i$ not conforming to $\pm \sum |c_i| \mathrm{MPE}_i$

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- independence of all quantities involved

$\Rightarrow$ apply Theorem to calculate risk of $\sum c_i Y_i$ not conforming to $\pm\sum |c_i| \mathrm{MPE}_i$

$\Rightarrow$ complies with the GUM [1, 2, 3] and ISO 17025 [9]

$\Rightarrow$ applicable also for small n and bounds of u_i, not so guidance in [1]

$\Rightarrow$ risks smaller than for distribution-free coverage intervals

Decision Rule I: Simplified

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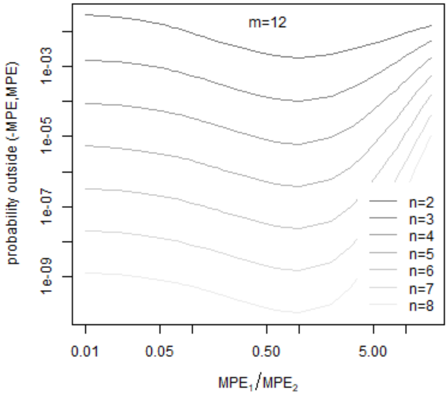
Decision rule I simplified:
tabulate risk for common settings

- $\text{MPE}_1 = \ldots = \text{MPE}_n$, $c_i = \pm 1$: depends only on n (and m)
- $\text{MPE}_2 = \ldots = \text{MPE}_n$, $c_i = \pm 1$: depends only on n, $\frac{\text{MPE}_1}{\text{MPE}_2}$ (and m)
- for small n
- ...



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Decision rule I assumes:

☑ measurements for each input Y_i conform to specification $\pm\mathrm{MPE}_i$
$\Rightarrow$ mandatory in conformity statements [9]

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Decision rule I assumes:

- ☑ measurements for each input Y_i conform to specification $\pm\text{MPE}_i$
  $\Rightarrow$ mandatory in conformity statements [9]
- ☑ conformity was established by an instrument
  with $X_i \sim N(0, u_i^2)$ and $u_i \leqslant \text{MPE}_i/m$ (for $m > 1$)
  $\Rightarrow$ available from calibration certificate for X_i with $k = 2$, or
  $\Rightarrow$ derive from decision rule for Y_i [6, 13]:
  - simple acceptance: often U limited with $k = 2$, e.g. $U \leqslant \text{MPE}/3$ [3]
  - guarded acceptance: e.g. $U \leqslant A_L - T_L$

Decision Rule I: Information Available

Decision rule I assumes:

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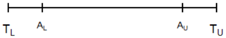

- ☐ $Y_i = X_i + U_i$ for each $i = 1, \ldots, n$
- ☐ independence of all quantities involved

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Decision rule II assumes:

- measurements for each input Y_i conform to specification $\pm \mathrm{MPE}_i$
- risk of non-conformance $\leqslant p_i$ for each input

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Decision rule II assumes:

- measurements for each input Y_i conform to specification $\pm \mathrm{MPE}_i$
- risk of non-conformance $\leqslant p_i$ for each input

$\Rightarrow \sum c_i Y_i$ conforms to $\pm \sum |c_i| \mathrm{MPE}_i$ if $\sum p_i$ small (see Lemma)

Lemma

Let $P\left(Y_i \notin y_i \pm MPE_i\right) = p_i$ and $c_i \neq 0$ for $i = 1, 2, \ldots$. Then the risk $P\left(\sum c_i Y_i \notin \sum c_i y_i \pm \sum |c_i| MPE_i\right) \leqslant \min\left(\sum p_i, 1\right)$ and equality may hold.

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Decision rule II assumes:

- measurements for each input Y_i conform to specification $\pm \mathrm{MPE}_i$
- risk of non-conformance $\leqslant p_i$ for each input

$\Rightarrow$ $\sum c_i Y_i$ conforms to $\pm \sum |c_i| \mathrm{MPE}_i$ if $\sum p_i$ small (see Lemma)

$\Rightarrow$ very simple, correlation may be unknown

$\Rightarrow$ complies with JCGM 106 [3] and ISO 17025 [9]

$\Rightarrow$ JCGM 100, 101 [1, 2] and distribution-free intervals not applicable

Lemma

Let $P\left(Y_i \notin y_i \pm MPE_i\right) = p_i$ and $c_i \neq 0$ for $i = 1, 2, \ldots$. Then the risk $P\left(\sum c_i Y_i \notin \sum c_i y_i \pm \sum |c_i| MPE_i\right) \leqslant \min\left(\sum p_i, 1\right)$ and equality may hold.

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Long vehicle weighing

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Long vehicle weighing

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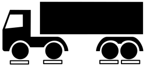
Traffic surveillance: overloaded vehicles prohibited

Example of axle load weighing instruments of class IIII [11] with 2.5t$<$mass$\leqslant$10t

- conform typically with MPE $=$ 100kg, $U \leqslant \frac{\text{MPE}}{6}$, often $k=2$ [12]

Scenario 1

- 4 instruments measure simultaneously (independence)
- decision rule I: risk of $\leqslant 6 \cdot 10^{-6}$ that the truck weigh measurement doesn't conform to $\pm$400kg



Long vehicle weighing

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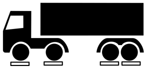

Scenario 2

- one instrument measures 4 times (unknown correl.)
- decision rule II with $p_i \leqslant 0.033$: there is a risk of $\leqslant 0.133$ that the truck weigh meas. doesn't conform to $\pm$400kg

☒ currently considered to conform under [15, 4] without limitations

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Conformity statements for linear combinations of quantities

- showed that knowledge only on conformity for each input is insufficient
- reviewed GUM guidance $\Rightarrow$ mostly applicable for info in calibr. certificates
- derived two risk-based decision rules
  - + tailored to little info in conformity statements of inputs (specifications and non-conformance risk or decision rule)
  - + simple to apply for common scenarios
  - + comply with JCGM 106 and ISO 17025
  - + apply to cases where the GUM [1, 2] is ill-suited or not applicable
- demonstrated need for new, risk-based decision rules in practice

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References

K. Klauenberg, J. Greenwood, and G. Foyer. Propagation of conformity statements in compliance with the GUM and ISO 17025. 2023. Draft available soon

Extension of decision rule I

- to fixed risks or other quantiles
- tabulate for other common, simple scenarios
- develop a WebApp for arbitrary MPE_i
- to inputs $Y_i = U_i^{(1)} + U_i^{(2)} + X_i$ whose conformity was derived by an instrument whose conformity was in turn established with limited uncert.

Discussion welcome on more needs for decision rules / conformity assessment

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Introduction

Review of Guidance
to Propagate Conformity Statements

Two Decision Rules
to Propagate Conformity Statements

Example

Summary and Outlook

Summary

Outlook

References

Conformity statements for linear combinations of quantities

- showed that knowledge only on conformity for each input is insufficient
- reviewed GUM guidance $\Rightarrow$ mostly applicable for info in calibr. certificates
- derived two risk-based decision rules
  - + tailored to little info in conformity statements of inputs (specifications and non-conformance risk or decision rule)
  - + simple to apply for common scenarios
  - + comply with JCGM 106 and ISO 17025
  - + apply to cases where the GUM [1, 2] is ill-suited or not applicable
- demonstrated need for new, risk-based decision rules