R49 EURO II Emission Calculation extensions

Dry exhaust gas is being sampled directly from the exhaust of a heavy 6-cylinder diesel engine. The engine is being tested to Euro II according to the R49 ESC test. The engine is fuelled on pure diesel in some modes, and on a mixture in which natural gas has been substituted for diesel in other modes. The dual fuel mixture is used in high-load modes.

R49 emission calculations that are specified separately for diesel and for natural gas are:

- Dry to wet concentration conversions
- Nox correction for ambient humidity
- Calculations of pollutant mass flows

These equations, referred to in the equations that follow by the codes A1, A2, …, are defined in Table 1. R49-revision 03, R49-revision 03 – amendment 01 and R49-revision 03 – amendment 02 versions of the R49 documents are identified in
Table 2.

Table 1 R49 Gaseous Emission Calculations

Ref	Description	Document	Annex	Appendix	Section	Item number
A1	Conversion of measurements in dry analyser to wet exhaust condition in C.I. engines	R49-03	4	3	1.1.2.1.1	-
A2	Conversion of measurements in dry analyser to wet exhaust condition in NG engines	R49-03	4	3	1.1.2.1.2	-
A3	Calculation of Nox mass flow in C.I. engines	R49-03	4	3	1.1.4	(1) undiluted
A4	Calculation of CO mass flow in C.I. engines	R49-03	4	3	1.1.4	(2) undiluted
A5	Calculation of HC mass flow in C.I. engines	R49-03	4	3	1.1.4	(3) undiluted
A6	Calculation of Nox mass flow in NG engines	R49-03	4	3	1.1.5	(1) undiluted
A7	Calculation of CO mass flow in NG engines	R49-03	4	3	1.1.5	(2) undiluted
A8	Calculation of HC mass flow in NG engines	R49-03	4	3	1.1.5	(3) undiluted
B1	Nox concentration correction for ambient air humidity in diesel engines	R49-03.1	4	2	4.2	(a)
B2	Nox concentration correction for ambient air humidity in gas engines	R49-03.1	4	2	4.2	(b)

Table 2 United Nations/ECE R49 Documents

Ref	*ECE document nr*	*Revision*	*Date*
R49-03	E/ECE/324 E/ECE/TRANS/505	Rev.1/Add.48/Rev.3	2 November 2000

R49-03.1	E/ECE/324 E/ECE/TRANS/505	Rev.1/Add.48/Rev.3/Amend.1	24 April 2002

DGI Extensions

Extensions to the R49 calculations, developed by DGI, are given below in section *Euro* II Calculations.
These equations calculate a weighted mean of the values for diesel and natural gas. The proportion of each fuel type in the dual fuel mixture is the weight factor.

1. Weighted mean of dry/wet converted pollutant concentrations. See Equation 3, below.
2. Weighted mean of mass flow calculations. See Equation 5, Equation 6 and Equation 7.

Discussion

Rationale for DGI Extensions
Brief justifications for the use of weighted means are supplied.

Weighted mean of dry/wet corrections

The correction to convert a dry measurement to a wet value compensates for water vapour that has been removed from the exhaust gas before the analyser sees it. Because diesel contains a smaller proportion of hydrogen than does natural gas, more water is produced per unit mass of natural gas than of diesel.

DGI calculates a weighted mean of the corrected concentrations that would have been obtained for an all-diesel and an all-natural gas test. The weighted mean combines the effects of the fuels in proportion to the amount of each being used by the engine.
Weighted mean of mass flow calculations
R49 specifies slightly different coefficients for the two fuels for calculation of mass flow given the concentrations of gaseous pollutants. The reason for the differences is not given.

DGI calculates a weighted mean of the mass flows that would have been calculated for an all-diesel and an all-natural gas test. The weighted mean combines the effects of the fuels in proportion to the amount of each being used by the engine.

Possible Objections

Mix-and-match of R49 specifications

DGI has taken specifications from R49-03 and R49-03.1 documents which span several years in time. The older document is used because it alone contains the Euro II specification. The newer document is used because its specification for Nox humidity correction is the only coherent one available. It may be argued that this use of multiple specifications is confusing and invalid.

Use of weighted means

DGI uses weighted means on the assumption that the effects of two different fuels, when combined into a single combustion chamber, are independent and can be added together in proportion to their mass. The chemistry of their combined combustion might be complicated, so that the assumption of independence is incorrect.

Double calculation

An alternative approach would be to omit the weighted mean of dry/wet corrections. Instead, the concentrations used in the final mass flow calculations can be the all-diesel and all-natural gas concentrations. The scheme now in use applies the weighted mean twice in series, and this may cause some distortion of results.

Euro II Calculations

Equation 1 – Definition of total mass flows, and proportion of gas substitution

$$G_{FUEL} = G_{DIESEL} + G_{GAS}$$

$$G_{EXH} = G_{FUEL} + G_{AIR}$$

$$S_{GAS} = \frac{G_{GAS}}{G_{FUEL}} * 100$$

Equation 2 – Dry to wet concentration conversions

Diesel (R49 calculation A1)

$$c_{NOx,wet,CI} = (1 - 1.85 * \frac{G_{FUEL}}{G_{AIR}}) * c_{NOx,dry}$$

$$c_{CO,wet,CI} = (1 - 1.85 * \frac{G_{FUEL}}{G_{AIR}}) * c_{CO,dry}$$

$$c_{THC,wet,CI} = (1 - 1.85 * \frac{G_{FUEL}}{G_{AIR}}) * c_{THC,dry}$$

$$c_{NMHC,wet,CI} = (1 - 1.85 * \frac{G_{FUEL}}{G_{AIR}}) * c_{NMHC,dry}$$

Natural gas (R49 calculation A2)

$$c_{NOx,wet,NG} = (1 - 3.15 * \frac{G_{FUEL}}{G_{AIR}}) * c_{NOx,dry}$$

$$c_{CO,wet,NG} = (1 - 3.15 * \frac{G_{FUEL}}{G_{AIR}}) * c_{CO,dry}$$

$$c_{THC,wet,NG} = (1 - 3.15 * \frac{G_{FUEL}}{G_{AIR}}) * c_{THC,dry}$$

$$c_{NMHC,wet,NG} = (1 - 3.15 * \frac{G_{FUEL}}{G_{AIR}}) * c_{NMHC,dry}$$

Equation 3 Weighted mean of wet pollutant concentrations, dual fuel

$$c_{NOx,wet} = (1 - \tfrac{S_{GAS}}{100}) * c_{NOx,wet,CI} + \tfrac{S_{GAS}}{100} * c_{NOx,wet,NG}$$
$$c_{CO,wet} = (1 - \tfrac{S_{GAS}}{100}) * c_{CO,wet,CI} + \tfrac{S_{GAS}}{100} * c_{CO,wet,NG}$$
$$c_{THC,wet} = (1 - \tfrac{S_{GAS}}{100}) * c_{THC,wet,CI} + \tfrac{S_{GAS}}{100} * c_{THC,wet,NG}$$
$$c_{NMHC,wet} = (1 - \tfrac{S_{GAS}}{100}) * c_{NMHC,wet,CI} + \tfrac{S_{GAS}}{100} * c_{NMHC,wet,NG}$$

Equation 4 – Nox humidity corrections

Diesel (R49 calculation B1)

$$c_{NOx,hum,CI} = \frac{1}{1 - 0.0182 * (H_a - 10.71)} * c_{NOx,wet}$$

Natural gas (R49 calculation B2)

$$c_{NOx,hum,NG} = \frac{1}{1 - 0.0329 * (H_a - 10.71)} * c_{NOx,wet}$$

Equation 5 – Weighted mean of Nox concentrations, humidity corrected, dual fuel

(Combines R49 calculations A3 and A6)

$$NOx_{mass} = ((1 - \tfrac{S_{GAS}}{100}) * 0.001587 * c_{NOx,hum,CI} + \tfrac{S_{GAS}}{100} * 0.001641 * c_{NOx,hum,NG})) * G_{EXH}$$

Equation 6 – Weighted mean of CO concentrations, dual fuel

(Combines R49 calculations A4 and A7)

$$CO_{mass} = ((1 - \tfrac{S_{GAS}}{100}) * 0.000966 + \tfrac{S_{GAS}}{100} * 0.001001)) * c_{CO,wet} * G_{EXH}$$

Equation 7 – Weighted means of hydrocarbon concentrations, dual fuel

(Combines R49 calculations A5 and A8)

$$THC_{mass} = ((1 - \tfrac{S_{GAS}}{100}) * 0.000478 + \tfrac{S_{GAS}}{100} * 0.000563) * c_{THC,wet} * G_{EXH}$$
$$NMHC_{mass} = ((1 - \tfrac{S_{GAS}}{100}) * 0.000478 + \tfrac{S_{GAS}}{100} * 0.000563) * c_{NMHC,wet} * G_{EXH}$$

Glossary

Symbols for Test Parameters

Symbol	Unit	Term
A_P	m²	Cross sectional area of the isokinetic sampling probe
A_T	m²	Cross sectional area of the exhaust pipe
CE_E	-	Ethane efficiency
CE_M	-	Methane efficiency

Symbol	Unit	Term
C1	-	Carbon 1 equivalent hydrocarbon
conc	ppm / vol%	Subscript denoting concentration
D_0	m^3/s	Intercept of PDP calibration function
DF	-	Dilution factor
D	-	Bessel function constant
E	-	Bessel function constant
E_Z	g/kWh	Interpolated NO_x emission of the control point
f_a	-	Laboratory atmospheric factor
f_c	s^{-1}	Bessel filter cut-off frequency
F_{FH}	-	Fuel specific factor for the calculation of wet concentration for dry concentration
F_S	-	Stoichiometric factor
G_{AIRW}	kg/h	Intake air mass flow rate on wet basis
G_{AIRD}	kg/h	Intake air mass flow rate on dry basis
G_{DILW}	kg/h	Dilution air mass flow rate on wet basis
G_{EDFW}	kg/h	Equivalent diluted exhaust gas mass flow rate on wet basis
G_{EXHW}	kg/h	Exhaust gas mass flow rate on wet basis
G_{FUEL}	kg/h	Fuel mass flow rate
G_{TOTW}	kg/h	Diluted exhaust gas mass flow rate on wet basis
H	MJ/m^3	Calorific value
H_{REF}	g/kg	Reference value of absolute humidity (10.71g/kg)
H_a	g/kg	Absolute humidity of the intake air
H_d	g/kg	Absolute humidity of the dilution air
HTCRAT	mol/mol	Hydrogen-to-Carbon ratio
i	-	Subscript denoting an individual mode
K	-	Bessel constant
k	m^{-1}	Light absorption coefficient
$K_{H,D}$	-	Humidity correction factor for NO_x for diesel engines
$K_{H,G}$	-	Humidity correction factor for NO_x for gas engines
K_V		CFV calibration function
$K_{W,a}$	-	Dry to wet correction factor for the intake air
$K_{W,d}$	-	Dry to wet correction factor for the dilution air
$K_{W,e}$	-	Dry to wet correction factor for the diluted exhaust gas
$K_{W,r}$	-	Dry to wet correction factor for the raw exhaust gas
L	%	Percent torque related to the maximum torque for the test engine
L_a	m	Effective optical path length
m		Slope of PDP calibration function
mass	g/h or g	Subscript denoting emissions mass flow (rate)

Symbol	Unit	Term
M_{DIL}	kg	Mass of the dilution air sample passed through the particulate sampling filters
M_d	mg	Particulate sample mass of the dilution air collected
M_f	mg	Particulate sample mass collected
$M_{f,p}$	mg	Particulate sample mass collected on primary filter
$M_{f,b}$	mg	Particulate sample mass collected on back-up filter
M_{SAM}	kg	Mass of the diluted exhaust sample passed through the particulate sampling filters
M_{SEC}	kg	Mass of secondary dilution air
M_{TOTW}	kg	Total CVS mass over the cycle on wet basis
$M_{TOTW,i}$	kg	Instantaneous CVS mass on wet basis
N	%	Opacity
N_P	-	Total revolutions of PDP over the cycle
$N_{P,i}$	-	Revolutions of PDP during a time interval
n	min^{-1}	Engine speed
n_P	s^{-1}	PDP speed
n_{hi}	min^{-1}	High engine speed
n_{lo}	min^{-1}	Low engine speed
n_{ref}	min^{-1}	Reference engine speed for ETC test
p_a	kPa	Saturation vapour pressure of the engine intake air
p_A	kPa	Absolute pressure
p_B	kPa	Total atmospheric pressure
p_d	kPa	Saturation vapour pressure of the dilution air
p_s	kPa	Dry atmospheric pressure
p_1	kPa	Pressure depression at pump inlet
P(a)	kW	Power absorbed by auxiliaries to be fitted for test
P(b)	kW	Power absorbed by auxiliaries to be removed for test
P(n)	kW	Net power non-corrected
P(m)	kW	Power measured on test bed
Ω	-	Bessel constant
Q_s	m^3/s	CVS volume flow rate
q	-	Dilution ratio
r	-	Ratio of cross sectional areas of isokinetic probe and exhaust pipe
R_a	%	Relative humidity of the intake air
R_d	%	Relative humidity of the dilution air
R_f	-	FID response factor
ρ	kg/m^3	Density
S	kW	Dynamometer setting
S_i	m^{-1}	Instantaneous smoke value

Symbol	Unit	Term
S_λ	-	λ-shift factor
T	K	Absolute temperature
T_a	K	Absolute temperature of the intake air
t	s	Measuring time
t_e	s	Electrical response time
t_f	s	Filter response time for Bessel function
t_p	s	Physical response time
Δt	s	Time interval between successive smoke data (= 1/sampling rate)
Δt_i	s	Time interval for instantaneous CFV flow
τ	%	Smoke transmittance
V_0	m³/rev	PDP volume flow rate at actual conditions
W	-	Wobbe index
W_{act}	kWh	Actual cycle work of ETC
W_{ref}	kWh	Reference cycle work of ETC
WF	-	Weighting factor
WF_E	-	Effective weighting factor
X_0	m³/rev	Calibration function of PDP volume flow rate
Y_i	m^{-1}	1 s Bessel averaged smoke value

Symbols for the Chemical Components

CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
CO	Carbon monoxide
DOP	Di-octylphtalate
CO_2	Carbon dioxide
HC	Hydrocarbons
NMHC	Non-methane hydrocarbons
Nox	Oxides of nitrogen
NO	Nitric oxide
NO_2	Nitrogen dioxide
PT	Particulates

Abbreviations

CFV	Critical flow venturi
CLD	Chemiluminescent detector

ELR	European Load Response Test
ESC	European Steady State Cycle
ETC	European Transient Cycle
FID	Flame Ionisation Detector
GC	Gas Chromatograph
HCLD	Heated Chemiluminescent Detector
HFID	Heated Flame Ionisation Detector
LPG	Liquefied Petroleum Gas
NDIR	Non-Dispersive Infrared Analyser
NG	Natural Gas
NMC	Non-Methane Cutter”
ISO 1585	Standard used to determine engine power