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Modelling of cold start emissions for passenger cars

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***MODELLING OF COLD START
EMISSIONS FOR PASSENGER CARS***

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Introduction

The Artemis (Assessment and Reliability of Transport Emission Models and Inventory Systems) study is aiming at developing a harmonised emission model for road, rail, air and ship transport to provide consistent emission estimates at the national, international and regional level.

The workpackage 300 entitled "Improved methodology for emission factor building and application to passenger cars and light duty vehicles" is aiming at improving the exhaust emission factors for the passenger cars and light duty vehicles, by investigating the accuracy of the emission measurements, by enlarging the emission factor data base especially for non-regulated pollutants, recent passenger cars and light duty vehicles, and by building emission factors according to the different purposes of Artemis.

One of the sub tasks of the workpackage 300, is aiming at modelling the cold start emissions of the passenger cars.

This report is the result of measurements made for the Artemis study and measurements made in a previous project (Joumard and Serié, 1999). The aim of this study consists in modelling the cold start impact on road vehicle emissions as functions of the pollutant and the vehicle type, using all the existing data in Europe. This model has been developed empirically considering the available data: excess emissions indeed, but also ambient temperature, start temperature, travelled distance and average speed. Measurements were made with passenger cars.

In the following analysis, the terms "cold effect" and "cold emissions" will be considered. There are five different ways of presenting cold effect results. These are:

- ✓ average cold emission factors (g/km) of the first (cold) cycle,
- ✓ absolute emissions (g) per cold cycle,
- ✓ the difference of average emission factors (g/km) between cold and hot cycles,
- ✓ the ratio of cold and hot emissions (relative cold emission),
- ✓ absolute excess cold start emissions (g) defined as the additional emission value obtained under cold conditions compared to the emission value that could have been recorded for the same period (cycle) under hot conditions.

In this report, cold-engine-related excess emissions are addressed.

1. Data

1.1. Initial data

In January 1994 an inquiry was sent to various laboratories studying vehicles emissions under cold start conditions. Data were obtained from TNO, INRETS, TU-Graz, TÜV, Politecnico di Milano, TRL, EMPA, INTA, VTT, VTI, KTI, LAT (see Annex 1 for laboratory acronyms). Information was asked about cold start tests: number of test vehicles, vehicle type and characteristics (fuel type, model year, engine capacity), driving cycle type, ambient temperature, start condition, emission measurements. Only a few number of laboratories were able to provide data relative to cold start, i.e. measuring cold and hot emissions over a same driving cycle.

16 770 emission factors measured with 1 378 passenger cars were collected. But only 15 616 emission factors measured with 1 229 passenger cars were kept for this work. The vehicles which have no emission standard or with a “US87” emission standard, were deleted from the database, because they cannot be considered as European emission standard. Data without both hot and cold emission factors were also deleted from the database.

In December 2002, the same inquiry was sent to the same laboratories to get new data. The data from the Artemis project was also added to the existing data. The list of available data is given in Annex 2.

A data represents one measurement for one vehicle during a cold cycle and a same hot cycle, independently of the pollutant recorded. Passenger cars were divided into ten categories:

- | | |
|------------------------------------|-------------------|
| ✓ Euro 0 gasoline without catalyst | ✓ Euro 2 gasoline |
| ✓ Euro 0 diesel without catalyst | ✓ Euro 2 diesel |
| ✓ Euro 0 gasoline with catalyst | ✓ Euro 3 gasoline |
| ✓ Euro 1 gasoline | ✓ Euro 3 diesel |
| ✓ Euro 1 diesel | ✓ Euro 4 gasoline |

Type	Name	Short Name	Duration (s)	Distance (m)	Average speed (km/h)
Standard	FTP72-1		505	5821	41.5
	ECE-15		780	4052	18.7
INRETS	Urbain Fluide Court	IUFC	189	999	19.0
	Route Court	IRC	126	1439	41.1

Table 1: Main characteristics of the various used cycles.

Cycle Name	Emission Standard	Fuel type	CO	CO ₂	FC	HC	NOx
ECE15-1	EURO0 CAT.	Gasoline	739	739		739	739
	EURO0 W/O CAT.	Gasoline	287	266	81	277	288
	EURO1	Diesel	3	3		3	3
		Gasoline	36	36		36	36
EURO2	Gasoline	26	26		26	26	
FTP72-1	EURO0 CAT.	Gasoline	727	727	10	727	727
	EURO0 W/O CAT.	Diesel	7	7	1	7	7
		Gasoline	16	16	16	16	16
	EURO1	Diesel	2	3	2	3	3
		Gasoline	3	3	3	3	3
	EURO2	Diesel	15	16	13	15	16
		Gasoline	5	5	5	5	5
	EURO3	Diesel	2	2	2	2	2
Gasoline		10	10	10	10	10	
IRC	EURO0 CAT.	Gasoline	10	10	10	10	10
	EURO0 W/O CAT.	Gasoline	17	16	10	17	17
	EURO1	Diesel	2	3	2	3	3
		Gasoline	4	4	4	4	4
	EURO2	Diesel	13	16	9	17	17
		Gasoline	8	7	7	3	7
	EURO3	Diesel	3	4	4	4	4
		Gasoline	11	12	6	10	12
IUFC	EURO0 CAT.	Gasoline	9	10	8	9	10
	EURO0 W/O CAT.	Gasoline	29	29	11	29	29
	EURO1	Diesel	2	3	2	3	2
		Gasoline	2	4	4	2	4
	EURO2	Diesel	27	29	10	28	28
		Gasoline	10	16	16	12	13
	EURO3	Diesel	3	4	4	4	4
		Gasoline	43	45	27	41	42
EURO4	Gasoline	7	7	7	7	7	

Table 2: Vehicle distribution versus average speed to calculate excess emission. To obtain the number of data, we have to multiply the number of vehicles by 2 for ECE15-1 and FTP72-1 cycle and by 15 for IUFC and IRC cycles.

For each vehicle, 2 types of cold and hot cycles were possibly followed (a short description of these cycles is shown in Table 1):

- ✓ Legislative cycles: ECE-15, FTP72-1.
- ✓ Inrets Short cycles: short free-flow urban (Inrets Urbain Fluide Court, so called IUFC) and short road (Inrets Route Court, so called IRC); each of these cycles was repeated 15 times. These cycles were drawn up from 23 000 travelled kilometres previously recorded all over France by 35 private cars (EUREV study, André, 1989; André, 1998; Joumard et coll., 1999).

Concerning excess emission data as a function of the cycle, the total number of obtained data was 29 825 (all categories and all pollutant merged). These data were measured with 1 556 vehicles. All samples were selected by various laboratories so that the distribution was representative, to some extent, of the fleet corresponding to each country. The number of vehicles tested by each laboratory and the corresponding cycles are shown in Table 2.

The annex 2 (Table 13, Table 14 and Table 15) detailed the Table 2 with the mean temperature of the measurements, the minimal and maximal temperature per cycle and per laboratory.

It should be noted that:

- ✓ for diesel cars with oxidation catalyst, the data are rare and do not allow a full data processing, as for other vehicle categories.
- ✓ for NO_x pollutant, some laboratories made standard humidity correction but not all of them. We did not take into account such a correction factor and we think it would be better to have data without humidity corrections, i.e. actual emissions. Concerning these latter, Annex 6 gives the computation of the humidity correction factor.

1.2. Data correction

Once all the data were collected, we had to take into account a number of parameters influencing the general method:

- ✓ Great variety of data:
 - as it can be seen in section 1.1, the number of vehicles analysed with standardised cycles is very significant; but such cycles are not representative since they do not reflect the reality. Comparing, for a same speed, the standard deviation of acceleration between Inrets and standard cycles [Joumard *et al.* (1995a)] yielded significantly differing results, acceleration standard deviation being lower than for standardised cycles.
 - the representative cycles (real cycles) enabled a fine description of the emission evolution, but there was a limited number of analysed vehicles.
- ✓ In the Table 2, we can see that some categories have not enough vehicles to make a good computation of the cold start. So we decided to merge some categories. The consequences are that some results will be the same for different categories.
- ✓ When the vehicles are tested using a standard cycle, the engine temperature is not always hot at the end of the cycle, according to Joumard *et al.* (1995b). Therefore, we had to introduce a light adjustment for each pollutant. Thus we obtained excess emissions over the entire cold period for different cycles, whether standard or not. Such an adjustment is needed especially for ECE-15-1 cycle since it is very short.
- ✓ Ambient temperature: it must be taken into account, if possible, whatever the mean speed may be. Therefore, we have to look for a relation independent of the average speed, considering that initially the starts are made with a cold engine (engine temperature corresponds to ambient temperature at start).
- ✓ We make the following hypothesis: excess emission depends on the engine start temperature only (as temperature parameter), this one being equal to the ambient temperature (real cold start) or greater than the ambient temperature (semi-cold or semi-hot engine). This hypothesis is necessary due to the lack of data.
- ✓ Taking into account the travelled distance after a cold start in order to decrease excess emission levels if the travelled distance is lower than the cold distance (i.e. the distance needed to stabilise the emission).

It should be noted that some measurements correspond to the same cycle. But, they correspond to measurements made by various laboratories using various measuring devices, in various conditions, with various car models, different vehicle ages, etc.. So it results in differences for the same cycles themselves.

1.3. Cold start excess emission and distance calculation

1.3.1. Methods for regulated pollutants

We propose hereafter to analyse the different methods used to calculate the cold start emissions and the cold start distances, when emission factor is a continuous signal. It is the case when instantaneous emissions are available, but also when a short cycle is repeated as long as the emissions are stabilized.

1.3.1.1. First method: Standard deviation

This method was developed at INRETS (Joumard and Serié, 1999). It consists in the calculation of the standard deviation of the emission factors from the last emission factor to the first. If the emissions are in the hot part, the standard deviation is quite stable with a slight decrease, but when the cold emissions appear the standard deviation increases rapidly.

The cold start distance is determined when the standard deviation changes in its form.

The cold start emission is calculated by integrating the emissions until the cold start distance.

Example:

The Figure 1 shows us the graphic representation of the emission of CO for Euro 1 Diesel at 18°C. On this figure we also plot the standard deviation. The standard deviation shows us that all the sub-cycles equal or higher than the sub-cycle 9 are hot. Thus the cold distance covers 8 sub cycles (i.e. 11.51 km). By integrating over the 8 first sub cycles we obtain the cold start emission of 0.89 g.

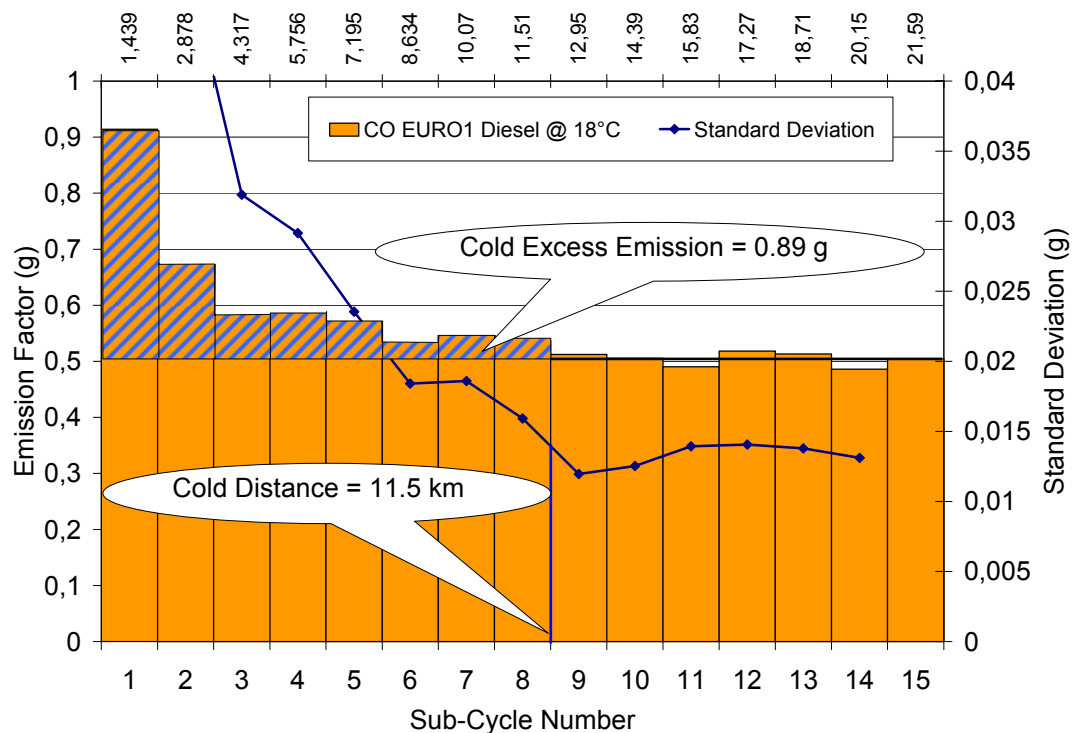


Figure 1: Example of cold start distance and emission calculation with the standard deviation method. The distance is in km and the emission in g per cycle.

1.3.1.2. Second method: Linear regression

This method was developed at EMPA (Weilenmann, 2001). It consists in the calculation of the linear regression of the cumulative emission factor over the points in the hot emission. The value of the regression at distance 0 gives the cold start emission.

The cold/hot limit is calculated by plotting two lines which are parallel to the linear regression. They have the same slope but the constant for the first one is 95% of the cold start emission and the second one 105%.

The last time the cumulative emission enters between these two lines is the cold start distance. Example:

The Figure 2 and the Figure 3 show us the graphic representation of the emission of CO for Euro 1 Diesel at 18°C. On this figure we also plot the cumulative emission, the cold start emission (0.89 g) calculated from the linear regression (we took the last 7 points because the cumulative emissions curve is like a straight line) and the two lines at 95% and 105% of the cold start emission. Thus the cold distance is 6.2 sub cycles (i.e. 8.92 km).

This second method can give slightly different results, in term of cold distance and cold excess emission. The problem of this method is the determination of the hot sub-cycles, over which the hot linear regression is calculated.

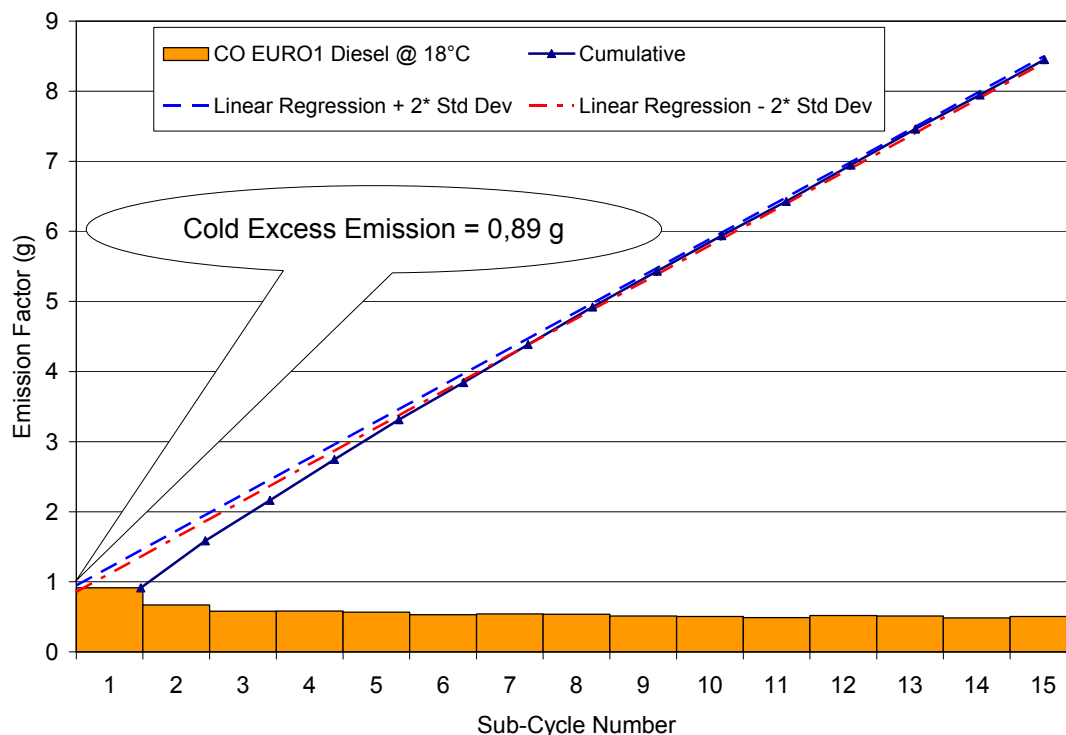


Figure 2: Example of cold start distance and emission calculation with the linear regression method.

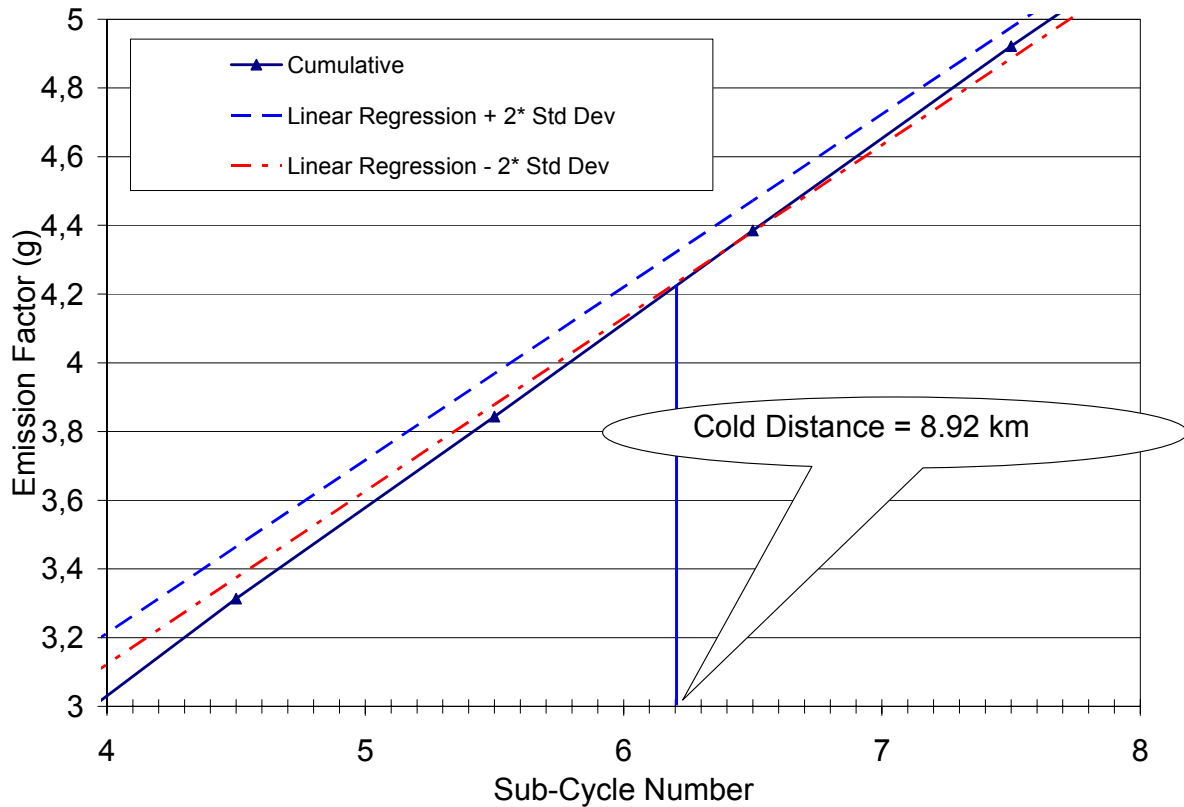


Figure 3: Example of cold start distance and emission calculation with the linear regression method.

1.3.1.3. Artemis method: Linear Regression + Standard deviation

This method was developed during the Artemis project. We mixed the two above methods. We first plot the emission, the cumulative emission and the standard deviation (see Figure 4 and Figure 5).

The main calculation is based on the linear regression method. The cold start emission is the value of the linear regression at distance 0.

But, to calculate the cold start distance, we look at the intersection of two lines (± 2 standard deviations around the hot emissions) with the emission factors curve.

To obtain the hot emissions, we look at the standard deviation of the emissions as in the first method. We obtain the distance where the emissions are surely hot. We calculate the hot emissions by averaging the emissions over these sub-cycles. We calculate the standard deviation of the hot emissions to obtain the two lines. When the emission factors curve “enters” for the last time between these two lines, we obtain the cold start distance.

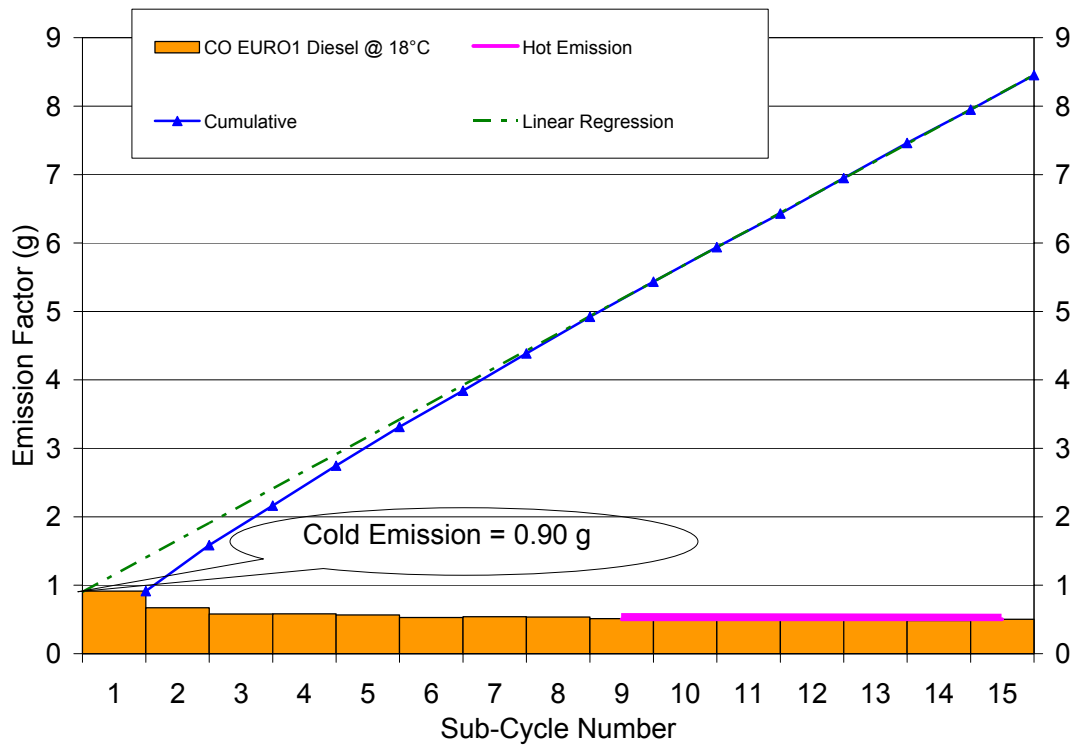


Figure 4: Example of cold start distance and emission calculation with the Artemis method. The graphic cold start emission is obtained at the sub-cycle “-0.5”.

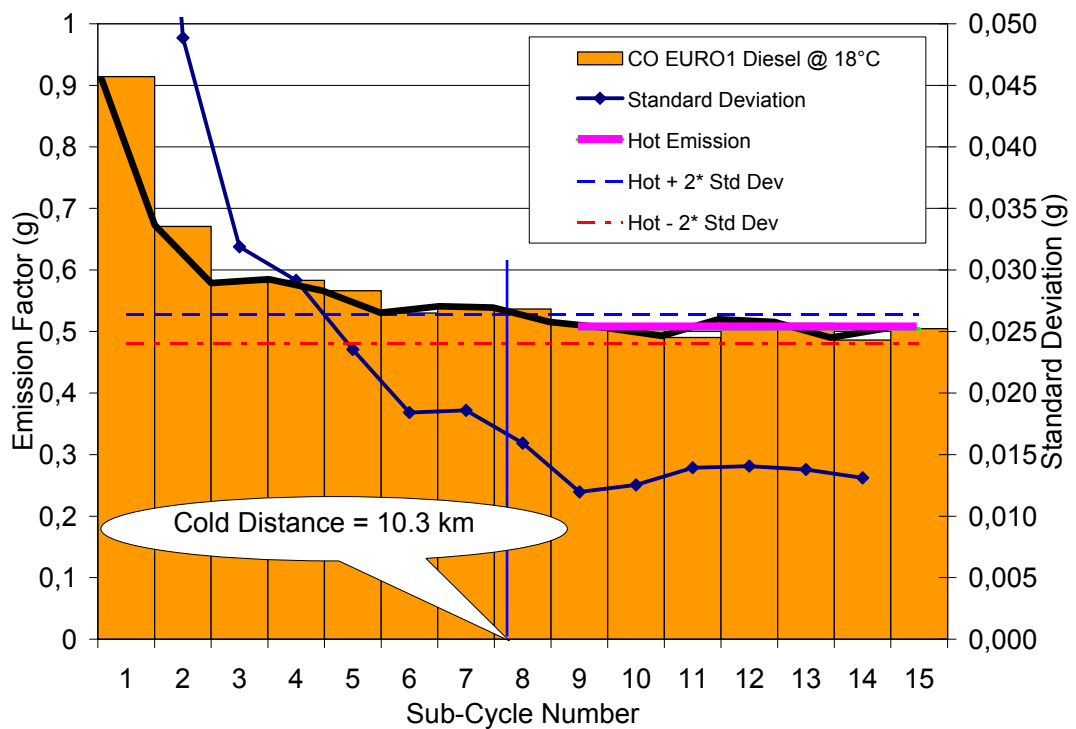


Figure 5: Example of cold start distance and emission calculation with the Artemis method.

1.3.1.4. Conclusion

The Table 3 shows us that the three methods give nearly the same cold start excess emission, but not the same cold start distance. The difference between cold distances goes up to 22 %.

Method	Standard deviation	Linear regression	Artemis
Cold distance (km)	11.5	8.9	10.3
Cold emission (g)	0.89	0.89	0.90

Table 3: Comparison of the cold start distance and the cold start emission calculated with the different methods.

With the third method, we can determine:

- ✓ When the cycle is completely hot as in the first method
- ✓ The cold start emission as in the second method but with more accuracy because we applied the linear regression with the hot emissions
- ✓ The cold start distance with a better accuracy because we are searching when the hot emission cuts the emission by looking at the standard deviation of the hot part.

1.3.2. Methods for non regulated pollutants

The emissions factors of the non regulated pollutants for the cold start conditions were only available with the short Inrets cycles. The emissions were measured with two different conditions. At INRETS the non regulated pollutants emission factors were measured with a cold short cycle and with a hot one. So the cold start excess emission is the difference between this two values because the cold short cycle is always hot at the end.

The others laboratories measured the non regulated pollutants emission factors with the same cycle. They have 3 emissions factors per cycle (1 per 5 sub cycles). So to calculate the excess emission, we consider that the cold distance is equivalent for each non regulated pollutant and for the total HC. The cold distance of HC is always less than 10 sub cycles (cf. Table 6).

With this condition, the excess emission is :

$$\begin{aligned} \text{Excess Emission} &= \text{EF}(\text{sub cycles 1 to 5}) - \text{EF}(\text{sub cycles 11 to 15}) \\ &+ \text{EF}(\text{sub cycles 6 to 10}) - \text{EF}(\text{sub cycles 11 to 15}) \end{aligned}$$

1.3.3. Results

1.3.3.1. Categories merging for temperature and the speed influence

As we could see in the Table 2, some categories have not enough vehicles to make a quite good computation of the temperature and the speed influence. So we decided to merge some categories for these computations. The Table 4 gives the changes made.

Old category	New category
EURO0 CAT./Gasoline	
EURO0 W/O CAT./Diesel	EURO0 W/O CAT./Gasoline-Diesel
EURO0 W/O CAT./Gasoline	
EURO1/Diesel	
EURO1/Gasoline	
EURO2/Diesel	
EURO2/Gasoline	
EURO3/Diesel	
EURO3/Gasoline	EURO3-EURO4/Gasoline
EURO4/Gasoline	

Table 4: Categories merging to allow computations over a greater number of vehicles.

As you would see, this merging is not applied for the calculation of the cold distance and the cold start excess emission of the Inrets short cycles. It is better to have the absolute cold start excess emission and absolute cold start distance.

1.3.3.2. ECE-15 emissions correction

A previous study (Joumard *et al.*, 1995b) showed that ECE-15 cycle could not cover entirely the cold period due to the cold start. So, we introduced a correction coefficient for this cycle to transform the measured excess emission during standard cycles into a full cold excess emission. This coefficient is deduced from measurement data recorded using IUFC cycle (because the mean speed is near the ECE-15 mean speed), which covers the whole cold period. Using this “cold” distance (see Table 6), calculated with the Artemis method, and the Inrets short cycles data, we calculate the correction coefficient to be applied to adjust the standardised cycles to the representative cycles.

For example (see Figure 6), the ECE-15 cycle corresponds to an average speed of 18.7 km/h and a distance of 4052 m. For CO pollutant, the cold distance (distance necessary to stabilise the emission level) is equal to 8.2 km for the representative cycle with the nearest average speed, i.e. 18.8 km/h (from Table 6). Regarding excess emission (normalised by the total excess emission) as a function of the distance, the ECE-15 cycle corresponds to 96 % of the total excess emission of the short free-flow urban cycle. Then the factor is equal to 1.04 ($=1/0.96$). We applied this method to all the pollutants and fuel consumption (see Table 5). The correction factors are sometimes important (from 0.74 to 4).

The majority of the correction factors are higher than 1, but sometimes lower than 1. A coefficient lower than 1 is possible when emission partially increasing with distance (rather than always increasing). An example for correction factor lower than 1 is shown in Annex 3.

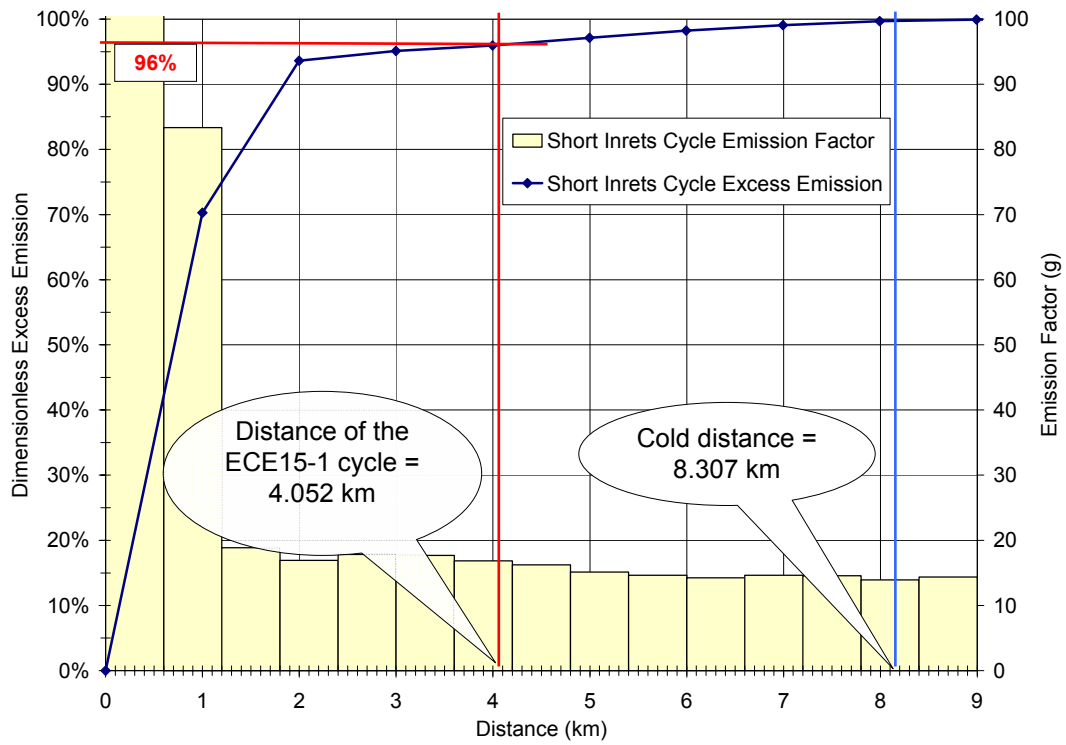


Figure 6: Cumulative dimensionless excess emission (ratio of absolute excess cold start emission to total absolute excess cold start emission) as a function of the distance (km) for short free-flow urban cycle. Correction calculation example of ECE-15 cycle for CO pollutant and gasoline cars without catalyst.

Old EU EM STD	Fuel type	Mean Temperature	CO	CO ₂	FC	HC	NO _x
EURO0 CAT.	Gasoline	16	1	1,104	1,052	1	1
		17	1	1	1	1	1
EURO0 W/O CAT.	Gasoline	-20	1,041	1,081	1	1,016	1,560
		-7	1	1,044	1	1,016	1,041
		10	1	0,971	1,009	1	1
		18	1	1	0,742	1	1
		21	0,810	0,812	1	1	1
EURO1	Diesel	18	1,242	1	1,116	1	4,002
		21	1	1,070	1	1,277	1
	Gasoline	16	1	1,149	1,072	1	0,983
		17	1	1	1	1	1
		20	1	1	1	0,978	1
EURO2	Diesel	-20	1,062	1,146	1	1,049	1,029
		-7	1,083	1,123	1	1,098	1
		22	1,074	1	1	1,118	-2,749
		23	1	1,111	1,081	1	1
	Gasoline	-20	1,003	1,347	1,112	1,010	1
		-8	1	1	1	1,006	1
		21	1	1,198	1,142	1	1
		23	1	1	1	0,983	1
EURO3	Diesel	22	1	1,124	1,119	0,936	1
		23	0,937	1	1	1	1
	Gasoline	-19	1	1,241	1	1,005	0,881
		-18	1	1	1,194	1	1
		-8	1,006	1,200	1,207	1,003	1
		22	1	1,101	1,159	1	1
23	1	1	1	0,999	1		
EURO4	Gasoline	-19	1,018	1,272	1,183	1,009	1
		-8	1,029	1,156	1,102	1,006	0,768
		23	1,029	1	1	1	0,774

Table 5: Correction factor of cold excess emission for ECE-15 cycle, to take into account the too short distance of the cycles.

Cycle	Emission Standard	Fuel type	Mean Temperature	CO	CO ₂	FC	HC	NOx	
IUFC	EURO0 CAT.	Gasoline	16		5,80	5,55	2,93	1,83	
			17	2,69					
	EURO0 W/O CAT.	Gasoline	-20	8,31	6,38		6,93	6,44	
			-7	2,88	4,85		5,43	8,97	
			10	3,96	5,19	5,19	1,26	3,41	
			18			6,96			
			21	6,31	7,21		2,23	0,58	
	EURO1	Diesel	18	8,74		6,82		8,23	
			21		7,73		8,66		
		Gasoline	16		4,46	4,54		4,92	
			17	3,60					
	EURO2	Diesel	20				5,97		
			-20	7,75	6,41		9,01	4,78	
			-7	6,63	7,32		9,56	2,86	
			22	5,85			8,04	9,87	
		Gasoline	23		7,50	6,46			
			-20	7,22	9,13	9,13	9,13	0,50	
			-8	3,70	2,66	2,82	5,89	0,93	
			21		8,42	8,43			
			23				7,49	1,00	
		EURO3	Diesel	25	1,83				
				22		7,14	7,12	6,36	2,41
			Gasoline	23	5,46				
	-19			1,71	8,59		9,84	9,08	
	-18					8,36			
	-8			4,14	9,02	9,42	9,70	0,90	
	EURO4	Gasoline	22		9,87	9,57			
			23	1,85			6,84	0,99	
	IRC	EURO0 CAT.	Gasoline	-19	8,70	8,62	8,62	9,81	1,24
				-8	7,88	6,17	6,23	9,74	8,41
EURO0 W/O CAT.		Gasoline	23	5,46	1,98	2,00	7,05	6,42	
			15	8,90	9,40	9,33	4,06	8,72	
EURO1		Diesel	13			12,08			
			17	12,04	13,65		12,40	1,51	
		18	10,57		9,38				
EURO2		Gasoline	21		14,11		13,25	12,06	
			17	2,74	7,86	8,56	5,04	7,58	
EURO3		Diesel	22		12,20	11,75	10,34	9,56	
			23	10,20					
		Gasoline	19	3,75	7,70	7,69		7,14	
			22				8,02		
EURO4		Diesel	22	9,53	5,72	5,71	5,36	3,67	
			21			7,69			
	Gasoline	22	2,86	10,85		9,34	1,40		

Table 6: Distance (km) necessary to warm up the engine according to the pollutant and the mean cycle speed (km/h). FC: Fuel consumption.

Cycle	Emission Standard	Fuel type	Mean Temperature	CO	CO ₂	FC	HC	NOx
IUFC	EURO0 CAT.	Gasoline	16		135	74.1	7.99	1.00
			17	58.3				
	EURO0 W/O CAT.	Gasoline	-20	296	391		72.4	1.95
			-7	173	178		32.1	0.201
			10	99.8	138	123	11.7	-0.154
			18			50.0		
			21	54.8	52.1		11.8	-0.223
	EURO1	Diesel	18	2.17		60.2		-0.113
			21		150		0.419	
		Gasoline	16		68.5	48.5		2.00
			17	28.9				
	EURO2	Diesel	20				8.52	
			-20	12.3	588		5.56	3.72
			-7	6.53	411		1.38	2.07
			22	2.85			0.431	-0.159
		Gasoline	23		147	42.9		
			-20	218	266	220	28.4	0.233
			-8	85.6	166	105	9.96	0.819
			21		139	56.4		
			23				3.97	0.848
			25	19.4				
	EURO3	Diesel	22		162	52.4	0.146	0.186
			23	2.09				
		Gasoline	-19	73.2	343		20.6	0.401
			-18			107		
			-8	40.6	285	105	9.19	0.436
			22		134	49.6		
23	8.49			1.45	0.486			
EURO4	Gasoline	-19	60.4	310	139	11.3	0.160	
		-8	52.4	180	90.4	7.75	0.123	
		23	5.42	73.8	26.6	0.645	0.172	
IRC	Diesel	EURO1	18	0.762		38.0		
			21		109		0.201	-0.346
		EURO2	22		143	44.3	0.252	0.129
			23	1.72				
	EURO3	22	1.73	158	50.8	0.151	0.900	
	Gasoline	EURO0 CAT.	15	51.8	102	61.7	4.81	2.11
		EURO0 W/O CAT.	13			100		
			17	95.0	135		10.1	-0.980
		EURO1	17	29.9	79.3	43.6	4.42	1.69
		EURO2	19	16.4	147	55.0		1.20
			22				3.14	
		EURO3	21			39.8		
	22	9.65	173		1.96	0.687		

Table 7: Cold start excess emission (g) according to the pollutant and the mean cycle speed (km/h). FC: Fuel consumption.

2. Influence of various parameters

In this chapter, the influence of the ambient temperature, average speed and distance on excess emissions will be shown. The aim is to express the excess emission as:

$$EE(T, V, \delta) = \omega_{20^{\circ}\text{C}, 20\text{km/h}} \cdot f(T, V) \cdot h(\delta) \quad (1)$$

with:

EE (T, V, δ) is the excess emission

T is the temperature

V is the average speed

$\delta = d/d_c$ is the dimensionless distance (travelled distance d divided by the cold distance d_c)

$\omega_{20^{\circ}\text{C}, 20\text{km/h}}$ is the excess emission at 20 °C and 20 km/h

$f(T, V) = \omega(T, V) / \omega_{20^{\circ}\text{C}, 20\text{km/h}}$ is the cycle speed and the temperature influence dimensionless function expressed in section 2.1

$h(\delta)$ is the distance influence function expressed in section 2.2

2.1. Excess emission as a function of the cycle speed and the temperature

In Figure 7, an example of CO₂ excess emission as a function of the mean speed for Euro 0 without catalyst gasoline vehicles is shown. The successive corrections are calculated and applied as follows:

- ✓ Merging the categories as explained in section 1.3.3.1.
- ✓ Data correction for ECE15-1 standard cycle, as explained in section 1.3.3.2.

Then, using modified data, we applied a 3D linear regression in order to obtain the excess emission level [g] as a function of the average speed V [km/h] and the temperature T [°C] (see Table 8 and figures in the annex 4).

It should be noticed that the regression is calculated using only four speed measurement points and different temperatures (the number of measurements points are indicated Table 8). One point in Figure 7 is the average of the excess emission for one temperature and one speed. But the regression was made by weighting each point by the number of vehicles. Using the calculated equations, we determined the correction coefficients (see Table 8) corresponding to the functions made dimensionless by dividing them by their values calculated at 20 km/h and 20°C. It should be noted that the boundaries of the measurements points for the linear regression calculation are [-20°C, +30°C] for the ambient temperature and [18 km/h, 42 km/h] for the mean speed. So outside these boundaries, the values of the regression have to be taken with care.

For all the data, fuel consumption was calculated using the carbon balance method. We used the formula (2) where the ratio hydrogen/carbon $r_{H/C}$ is equal to 1.8 for gasoline (leaded or unleaded) and 2.0 for diesel. The HC mass has to be expressed in CH₄ equivalent.

$$\frac{\text{Fuel mass}}{12.011 + 1.008 \cdot r_{H/C}} = \frac{\text{CO}_2 \text{ mass}}{44.011} + \frac{\text{CO mass}}{28.011} + \frac{\text{HC mass}}{16.043} + \frac{\text{Particle mass}}{12.011} \quad (2)$$

(Joumard *et al.*, 1995b)

This equation indicates that the CO₂ emission is not the only factor of the fuel consumption. Joumard *et al.* (1990) showed, for gasoline vehicles without catalyst, that the fuel conversion rates respectively into CO₂, CO and HC equals on average 78 %, 19 % and 4 %, with little variations depending on average speed. Of course, for vehicles emitting much less regulated pollutants (as 3 way catalyst vehicles or diesel powered vehicles), CO₂ rate is much higher.

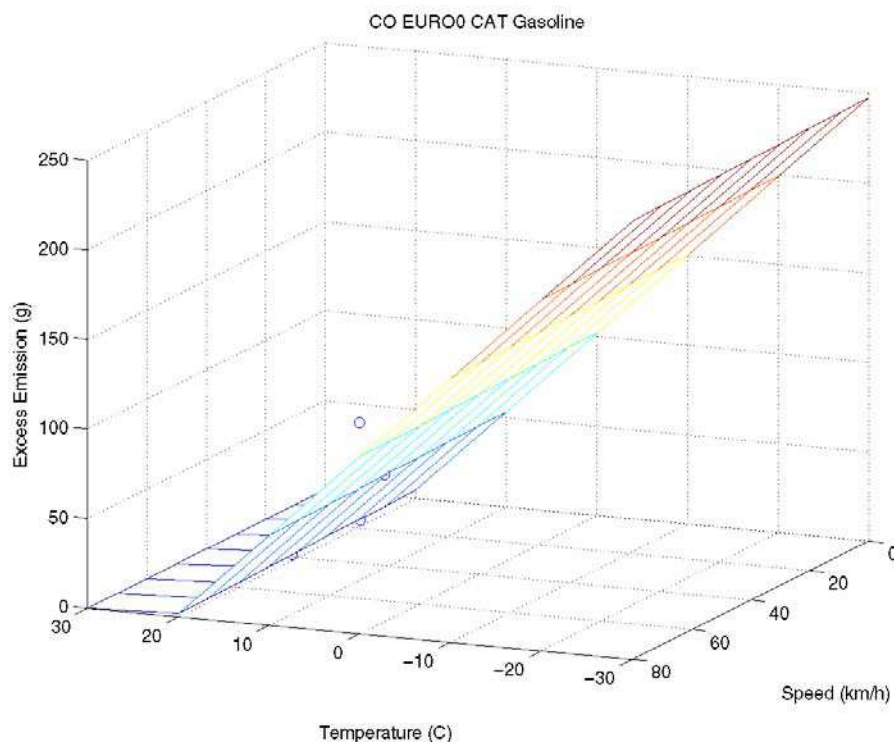


Figure 7: Example of CO excess emission as a function of the mean speed and the temperature for Euro 0 without catalyst gasoline vehicles.

Pollutant	Standard Emission	Fuel Type	# of points	Excess Emission Equation $\omega(T,V)$	Correction Coefficient $f(T,V)$	MDC	TDC	VDC	Typical Error
CO	EURO0 CAT.	Gasoline	4	$102,191 - 4,865 * T - 0,042 * V$	$25,227 - 1,201 * T - 0,01 * V$	0,6827	0,4661	0,4653	4,2528
	EURO0 W/O CAT.	Gasoline/Diesel	9	$67,17 - 5,624 * T + 2,462 * V$	$17,155 - 1,436 * T + 0,629 * V$	0,8737	0,7633	0,7620	23,4155
	EURO1	Diesel	4	$2,864 + 0,039 * T - 0,077 * V$	$1,363 + 0,019 * T - 0,037 * V$	0,9615	0,9244	0,8992	0,2312
		Gasoline	4	$28,149 + 0,72 * T - 0,47 * V$	$0,849 + 0,022 * T - 0,014 * V$	0,8543	0,7298	0,7169	3,2999
	EURO2	Diesel	5	$8,143 - 0,202 * T - 0,077 * V$	$3,172 - 0,079 * T - 0,03 * V$	0,9587	0,9192	0,9161	1,0639
		Gasoline	6	$13,112 - 0,429 * T + 0,174 * V$	$1,636 - 0,054 * T + 0,022 * V$	0,1553	0,0241	-0,0193	34,2348
	EURO3	Diesel	3	$2,948 - 0,044 * V$	$1,431 - 0,022 * V$	0,6350	0,4032	0,1370	0,6719
EURO3/EURO4	Gasoline	8	$37,092 - 1,46 * T - 0,054 * V$	$5,448 - 0,214 * T - 0,008 * V$	0,9749	0,9505	0,9490	6,0010	
CO ₂	EURO0 CAT.	Gasoline	4	$198,07 - 8,081 * T - 0,375 * V$	$6,842 - 0,279 * T - 0,013 * V$	0,6563	0,4308	0,4300	8,7143
	EURO0 W/O CAT.	Gasoline/Diesel	9	$113,613 - 6,83 * T + 2,181 * V$	$5,506 - 0,331 * T + 0,106 * V$	0,8542	0,7297	0,7280	30,5919
	EURO1	Diesel	4	$194,797 + 1,709 * T - 4,099 * V$	$1,325 + 0,012 * T - 0,028 * V$	0,7416	0,5499	0,4499	39,2526
		Gasoline	4	$83,605 + 0,755 * T - 1,108 * V$	$1,092 + 0,01 * T - 0,014 * V$	0,5061	0,2561	0,2223	12,2199
	EURO2	Diesel	5	$405,016 - 10,311 * T - 2,868 * V$	$2,864 - 0,073 * T - 0,02 * V$	0,9608	0,9232	0,9206	48,4942
		Gasoline	6	$132,266 + 1,758 * T - 1,811 * V$	$1,008 + 0,013 * T - 0,014 * V$	0,4183	0,1750	0,1420	47,6549
	EURO3	Diesel	3	$-113,973 + 16 * T - 2,295 * V$	$-0,712 + 0,1 * T - 0,014 * V$	0,4490	0,2016	-0,0265	59,3968
EURO3/EURO4	Gasoline	8	$246,601 - 5,026 * T - 1,016 * V$	$1,961 - 0,04 * T - 0,008 * V$	0,8934	0,7982	0,7925	47,5357	
FC	EURO0 CAT.	Gasoline	3	$8111,98 - 280,486 * T - 127,594 * V$	$-163,437 + 5,651 * T + 2,571 * V$	1	1	1	0
	EURO0 W/O CAT.	Gasoline/Diesel	7	$70,624 - 1,997 * T + 0,133 * V$	$2,119 - 0,06 * T + 0,004 * V$	0,6083	0,3700	0,3647	25,1778
	EURO1	Diesel	3	$43,66 + 2,5 * T - 1,744 * V$	$0,743 + 0,043 * T - 0,03 * V$	0,8155	0,6650	0,4416	18,3815
		Gasoline	3	$-19,045 + 3,587 * T - 0,221 * V$	$-0,395 + 0,074 * T - 0,005 * V$	1	1	1	0
	EURO2	Diesel	3	$701,177 - 32 * T - 0,941 * V$	$16,55 - 0,755 * T - 0,022 * V$	0,5457	0,2978	0,2494	15,6896
		Gasoline	5	$128,974 - 2,824 * T - 0,913 * V$	$2,378 - 0,052 * T - 0,017 * V$	0,8546	0,7303	0,7078	22,1920
	EURO3	Diesel	3	$26,796 + 2 * T - 0,743 * V$	$0,516 + 0,039 * T - 0,014 * V$	0,4574	0,2092	-0,0167	18,7913
EURO3/EURO4	Gasoline	8	$104,887 - 1,728 * T - 1,221 * V$	$2,284 - 0,038 * T - 0,027 * V$	0,9550	0,9120	0,9082	11,7696	

Pollutant	Standard Emission	Fuel Type	# of points	Excess Emission Equation $\omega_{T,V}$	Correction Coefficient $f(T,V)$	MDC	TDC	VDC	Typical Error
HC	EURO0 CAT.	Gasoline	4	$9,177 - 0,419*T - 0,004*V$	$12,893 - 0,589*T - 0,006*V$	0,5148	0,2650	0,2640	0,5705
	EURO0 W/O CAT.	Gasoline/Diesel	9	$20,406 - 1,244*T + 0,23*V$	$158,58 - 9,666*T + 1,787*V$	0,8627	0,7442	0,7428	5,2385
	EURO1	Diesel	4	$0,502 + 0,009*T - 0,014*V$	$1,235 + 0,022*T - 0,034*V$	0,9054	0,8198	0,7797	0,0697
		Gasoline	4	$8,169 + 0,246*T - 0,223*V$	$0,946 + 0,029*T - 0,026*V$	0,9900	0,9802	0,9792	0,2380
	EURO2	Diesel	5	$2,321 - 0,098*T - 0,005*V$	$9,034 - 0,382*T - 0,02*V$	0,8891	0,7905	0,7831	0,7509
		Gasoline	6	$4,06 - 0,004*T - 0,06*V$	$1,461 - 0,001*T - 0,022*V$	0,1267	0,0160	-0,0308	4,5144
	EURO3	Diesel	3	$0,551 - 0,019*T - 0,002*V$	$3,797 - 0,128*T - 0,012*V$	0,3789	0,1436	-0,1011	0,0554
EURO3/EURO4	Gasoline	8	$8,395 - 0,393*T + 0,008*V$	$12,335 - 0,578*T + 0,011*V$	0,9350	0,8743	0,8708	2,6069	
NOx	EURO0 CAT.	Gasoline	4	$4,076 - 0,19*T - 0,002*V$	$16,556 - 0,771*T - 0,007*V$	0,9274	0,8600	0,8598	0,0625
	EURO0 W/O CAT.	Gasoline/Diesel	9	$0,796 - 0,029*T - 0,016*V$	$-7,683 + 0,278*T + 0,157*V$	0,7482	0,5598	0,5573	0,2244
	EURO1	Diesel	4	$0,52 - 0,028*T - 0,004*V$	$-4,317 + 0,233*T + 0,033*V$	0,9686	0,9382	0,9228	0,1224
		Gasoline	4	$1,427 + 0,067*T - 0,034*V$	$0,686 + 0,032*T - 0,016*V$	0,9736	0,9479	0,9455	0,1516
	EURO2	Diesel	5	$1,363 - 0,09*T + 0,013*V$	$-7,335 + 0,484*T - 0,067*V$	0,9897	0,9796	0,9789	0,1777
		Gasoline	6	$0,467 + 0,024*T - 0,005*V$	$0,561 + 0,028*T - 0,006*V$	0,7151	0,5113	0,4905	0,3260
	EURO3	Diesel	3	$-0,565 + 0,02*T + 0,019*V$	$-2,693 + 0,093*T + 0,092*V$	0,5620	0,3159	0,1204	0,3681
EURO3/EURO4	Gasoline	8	$0,484 + 0,002*T - 0,004*V$	$1,07 + 0,005*T - 0,009*V$	0,1857	0,0345	0,0061	0,2157	

Table 8: Equation describing the influence of mean speed V [km/h] and ambient temperature T [°C] on excess emission $\omega(T,V)$ [g] and the associated dimensionless correction coefficients $f(V,T)$. This equation results in a 3D linear regression (best fitted plan). These equations must be applied with the positive results. MDC=Multiple determination coefficient, TDC= Temperature determination coefficient, VDC = Speed determination coefficient.

2.2. Excess emission as a function of the travelled distance

The knowledge of the emission evolution during the cold phase, by considering the emissions measured on each Inrets short cycles, allows us to model the excess emission according to the travelled distance. The excess emission is therefore increasing till the end of the cold distance, and then equal to the cold start excess emission presented in section 2.1.

In a first step, we model the cold distance d_c as a function of the vehicle speed V and the ambient temperature T by a 3D linear regression (see Table 9 and an example Figure 8; the others ones are in annex 5). Both excess emission and cold distance are therefore expressed as function of V and T .

It allows us to make dimensionless both excess emission and travelled distance (see an example Figure 9; the others ones in annex 6) and to look at the influence of the dimensionless travelled distance $\delta=d/d_c$ on the dimensionless excess emission. We express this influence as an exponential function $h(\delta)$. It should be noted that the chosen exponential function is well representative of the majority of the data. But in some cases, especially for NOx, the shape is much more complex (as shown in Annex 5.5). As we prefer to model only the influence of the distance, we propose to use the exponential function in all the cases.

This function $h(\delta)$ could be influenced by two available parameters, i.e. the ambient temperature T and the average speed V . But in fact the influence of V is very low and we consider only the influence of T . Therefore $h(\delta)$ can be expressed as:

$$h(\delta) = \frac{1 - e^{a(T) \cdot \delta}}{1 - e^{a(T)}} \quad \text{with} \quad \delta = \frac{d}{d_c} \quad (3)$$

where $a(T)$ corresponds to the temperature dependence of dimensionless excess emission. $a(T)$ is given in Table 10 for the different vehicle categories: we choose for $a(T)$ a linear regression.

The equations for each category are given in Table 10.

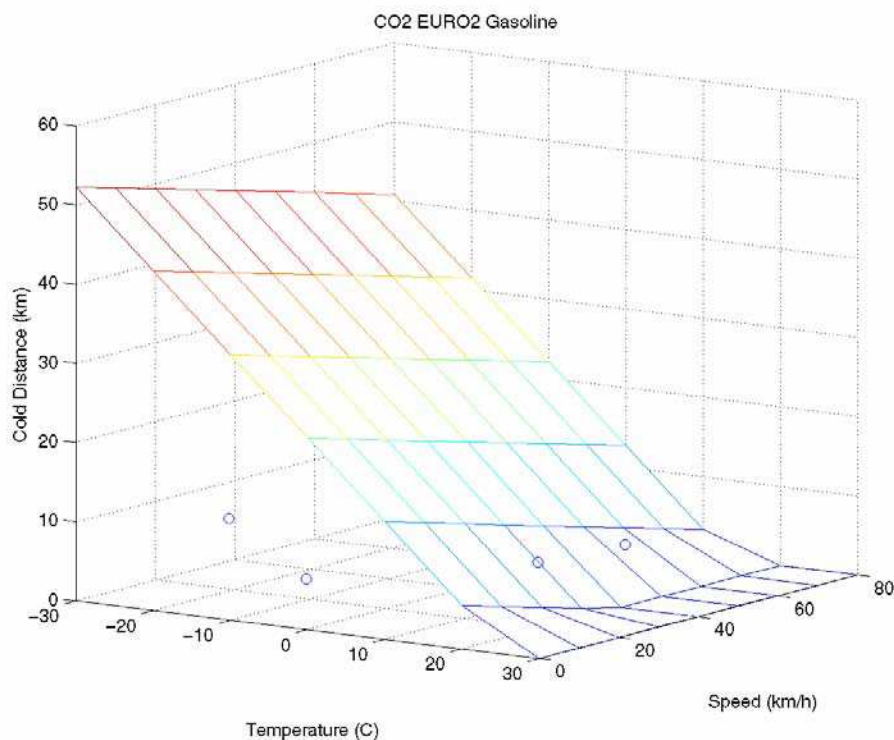


Figure 8: Cold distance d_c (km) as a function of the vehicle mean speed V (km/h) and the ambient temperature T ($^{\circ}\text{C}$) for CO_2 pollutant on Euro 2 gasoline car.

Pollutant	Standard Emission	Fuel type	# of points	d_c (T,V)	MDC	TDC	VDC	Typical error
CO	EURO0 CAT.	Gasoline	2	$24,146 - 0,937*T - 0,143*V$	1	1	1	0
	EURO0 W/O CAT.	Gasoline/Diesel	5	$-0,415 - 0,016*T + 0,311*V$	0,900	0,810	0,801	1,595
	EURO1	Diesel	2	$4,666 + 0,125*T + 0,083*V$	1	1	1	0
		Gasoline	2	$7,312 - 0,148*T - 0,039*V$	1	1	1	0
	EURO2	Diesel	4	$2,84 - 0,041*T + 0,199*V$	0,994	0,989	0,988	0,204
		Gasoline	4	$1,997 - 0,099*T + 0,091*V$	0,924	0,854	0,833	0,561
EURO3	Diesel	2	$1,319 + 0,031*T + 0,185*V$	1	1	1	0	
EURO3/EURO4	Gasoline	7	$2,784 - 0,035*T + 0,019*V$	0,306	0,093	0,062	1,808	
CO ₂	EURO0 CAT.	Gasoline	2	$-2,8 + 0,192*T + 0,25*V$	1	1	1	0
	EURO0 W/O CAT.	Gasoline/Diesel	5	$-0,166 + 0,027*T + 0,323*V$	0,982	0,964	0,962	0,729
	EURO1	Diesel	2	$-9,013 + 0,563*T + 0,289*V$	1	1	1	0
		Gasoline	2	$0,917 + 0,031*T + 0,154*V$	1	1	1	0
	EURO2	Diesel	4	$3,098 + 0,021*T + 0,211*V$	0,997	0,994	0,994	0,192
		Gasoline	4	$7,019 + 0,09*T - 0,027*V$	0,611	0,373	0,307	1,396
EURO3	Diesel	2	$17,427 - 0,453*T - 0,064*V$	1	1	1	0	
EURO3/EURO4	Gasoline	7	$7,342 + 0,018*T + 0,077*V$	0,503	0,253	0,228	1,482	
FC	EURO0 CAT.	Gasoline	2	$-11,836 + 0,494*T + 0,395*V$	1	1	1	0
	EURO0 W/O CAT.	Gasoline/Diesel	3	$-2,535 + 0,178*T + 0,312*V$	1	1	1	0
	EURO1	Diesel	2	$-16,636 + 1,063*T + 0,116*V$	1	1	1	0
		Gasoline	2	$0,448 + 0,031*T + 0,182*V$	1	1	1	0
	EURO2	Diesel	2	$51,89 - 2,5*T + 0,24*V$	1	1	1	0
		Gasoline	4	$7,108 + 0,087*T - 0,028*V$	0,610	0,372	0,306	1,361
EURO3	Diesel	2	$10,515 - 0,109*T - 0,064*V$	1	1	1	0	
EURO3/EURO4	Gasoline	7	$9,354 + 0,008*T - 0,044*V$	0,184	0,034	-0,018	1,813	

Pollutant	Standard Emission	Fuel type	# of points	$d_c(T,V)$	MDC	TDC	VDC	Typical error
HC	EURO0 CAT.	Gasoline	2	$-9,474 + 0,399*T + 0,232*V$	1	1	1	0
	EURO0 W/O CAT.	Gasoline/Diesel	5	$-5,393 - 0,128*T + 0,495*V$	0,988	0,977	0,976	0,719
	EURO1	Diesel	2	$16,575 - 0,594*T + 0,208*V$	1	1	1	0
		Gasoline	2	$6,775 + 0*T + -0,042*V$	1	1	1	0
	EURO2	Diesel	4	$6,791 - 0,033*T + 0,102*V$	0,973	0,948	0,945	0,236
		Gasoline	4	$6,758 + 0,007*T + 0,027*V$	0,365	0,133	-0,024	0,823
	EURO3	Diesel	2	$12,23 - 0,25*T - 0,046*V$	1	1	1	0
EURO3/EURO4	Gasoline	7	$6,468 - 0,08*T + 0,109*V$	0,983	0,966	0,965	0,251	
NOx	EURO0 CAT.	Gasoline	2	$-79,174 + 2,623*T + 1,5*V$	1	1	1	0
	EURO0 W/O CAT.	Gasoline/Diesel	5	$4,48 - 0,18*T + 0,015*V$	0,915	0,838	0,830	1,198
	EURO1	Diesel	2	$1,497 + 0,172*T + 0,173*V$	1	1	1	0
		Gasoline	2	$2,622 + 0*T + 0,121*V$	1	1	1	0
	EURO2	Diesel	4	$6,588 + 0,16*T - 0,006*V$	0,937	0,878	0,872	0,959
		Gasoline	4	$-4,424 + 0,007*T + 0,278*V$	1	0,999	0,999	0,075
	EURO3	Diesel	2	$-4,291 + 0,281*T + 0,057*V$	1	1	1	0
EURO3/EURO4	Gasoline	7	$3,286 - 0,124*T + 0,014*V$	0,625	0,390	0,369	2,742	

Table 9: Formula describing the cold distance d_c (km) as a function of the average speed V (km/h) and the temperature T (°C). The results of this formula must be positive.

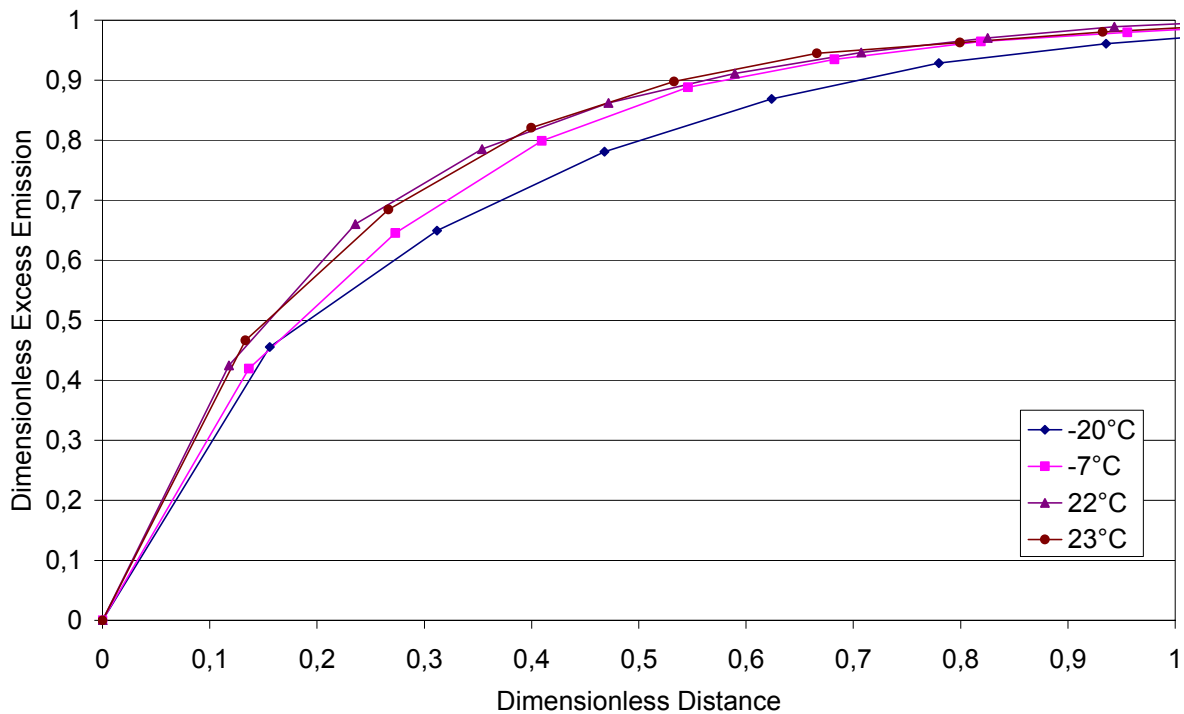


Figure 9: Temperature influence on the dimensionless excess emission for Euro 2 diesel cars on CO₂ pollutant, according to the dimensionless distance.

Pol.	EU_emis_standard	Fuel type	a(T)	Pol.	EU_emis_standard	Fuel type	a(T)
CO	EURO0 CAT.	Gasoline	3,0117*T -57,052	HC	EURO0 CAT.	Gasoline	-0,5797*T + 3,104
	EURO0 W/O CAT.	Gasoline	-0,138*T -7,166		EURO0 W/O CAT.	Gasoline	0,0617*T -4,971
	EURO1	Diesel	-3,535		EURO1	Diesel	-3,647
		Gasoline	-6,487			Gasoline	-1,6153*T + 22,951
	EURO2	Diesel	0,013*T -4,769		EURO2	Diesel	0,0365*T -5,367
		Gasoline	0,0708*T -7,066			Gasoline	-0,1755*T -10,790
	EURO3	Diesel	4,942*T -123,364		EURO3	Diesel	-5,619
		Gasoline	-0,0105*T -5,719			Gasoline	-0,0765*T -10,936
EURO4	Gasoline	0,0453*T -6,115	EURO4	Gasoline	-0,2763*T -14,426		
CO ₂	EURO0 CAT.	Gasoline	0,1929*T -6,629	NOx	EURO0 CAT.	Gasoline	0,8063*T -15,710
	EURO0 W/O CAT.	Gasoline	-0,0261*T -4,351		EURO0 W/O CAT.	Gasoline	-0,1459*T -5,324
	EURO1	Diesel	-5,131		EURO1	Diesel	-0,4953*T + 7,777
		Gasoline	-0,7775*T + 10,367			Gasoline	-1,3613*T + 13,946
	EURO2	Diesel	-0,0188*T -3,926		EURO2	Diesel	0,0837*T -3,029
		Gasoline	-0,0182*T -2,658			Gasoline	0,1006*T -4,617
	EURO3	Diesel	-3,208		EURO3	Diesel	-2,626
		Gasoline	-0,0217*T -4,228			Gasoline	0,8659*T -16,396
EURO4	Gasoline	0,0396*T -2,583	EURO4	Gasoline	-0,4427*T -60,590		
FC	EURO0 CAT.	Gasoline	0,312*T -9,427				
	EURO0 W/O CAT.	Gasoline	-0,2066*T -3,223				
	EURO1	Diesel	-3,601				
		Gasoline	-0,7282*T + 8,510				
	EURO2	Diesel	-0,0924*T -2,075				
		Gasoline	0,0092*T -3,516				
	EURO3	Diesel	-3,236				
		Gasoline	0,0033*T -3,870				
EURO4	Gasoline	0,0484*T -2,986					

Table 10: Equation describing the temperature influence on the dimensionless excess emission as a function of the dimensionless distance δ ($\delta=d/d_0$).

2.3. General formula of cold-start-related excess emissions of a trip

We assumed that the general model of the cold start emission is a function of ambient temperature, average speed and travelled distance. Measurements were made using different cycles, these being characterised by their mean speed (see Table 1). The cycles can be characterised by other parameters such as mean product speed times acceleration (dynamics measurement), standard deviation of speed or standard deviation of the product speed times acceleration for example (Hassel and Weber, 1996). But, those parameters can not be used in the general model due to the fact that there is no available statistics.

With the calculation made in section 2, the equation (1) can be written as:

$$EE(T, V, \delta) = \omega_{20^{\circ}\text{C}, 20\text{km/h}} \cdot f(T, V) \cdot \left\{ \frac{1 - e^{a(T)\delta}}{1 - e^{a(T)}} \right\}$$

where:

EE: Excess emission for a trip in g

V: mean speed in km/h during the cold period

T: temperature in °C (ambient temperature for cold start, engine start temperature for starts at an intermediate temperature)

$\delta = \frac{d}{d_c(T, V)}$ the dimensionless distance

with d: the travelled distance
d_c: the cold distance

$\omega_{20^{\circ}\text{C}, 20\text{km/h}}$: reference excess emission (at 20 °C and 20 km/h).

The function $\omega_{20^{\circ}\text{C}, 20\text{km/h}}$, $f(T, V)$, $a(T)$, $d_c(T, V)$ can be found respectively in Table 11, Table 8, Table 10 and Table 9. The function f must be positive or null.

Pollutant	Emission Standard	Fuel type	$\omega_{20^{\circ}\text{C},20\text{km/h}}$ (g)	Pollutant	Emission Standard	Fuel type	$\omega_{20^{\circ}\text{C},20\text{km/h}}$ (g)
CO	EURO0 CAT.	Gasoline	4,051	HC	EURO0 CAT.	Gasoline	0,712
	EURO0 W/O CAT.	Gasoline/Diese 1	3,916		EURO0 W/O CAT.	Gasoline/Diese 1	0,129
	EURO1	Diesel	2,102		EURO1	Diesel	0,407
		Gasoline	33,149			Gasoline	8,640
	EURO2	Diesel	2,567		EURO2	Diesel	0,257
		Gasoline	8,012			Gasoline	2,779
	EURO3	Diesel	2,059		EURO3	Diesel	0,145
EURO3/EURO4	Gasoline	6,809	EURO3/EURO4	Gasoline	0,681		
CO ₂	EURO0 CAT.	Gasoline	28,950	NOx	EURO0 CAT.	Gasoline	0,246
	EURO0 W/O CAT.	Gasoline/Diese 1	20,636		EURO0 W/O CAT.	Gasoline/Diese 1	-0,104
	EURO1	Diesel	147,015		EURO1	Diesel	-0,121
		Gasoline	76,536			Gasoline	2,082
	EURO2	Diesel	141,435		EURO2	Diesel	-0,186
		Gasoline	131,220			Gasoline	0,834
	EURO3	Diesel	160,132		EURO3	Diesel	0,210
EURO3/EURO4	Gasoline	125,769	EURO3/EURO4	Gasoline	0,452		
FC	EURO0 CAT.	Gasoline	-49,634				
	EURO0 W/O CAT.	Gasoline/Diese 1	33,335				
	EURO1	Diesel	58,785				
		Gasoline	48,267				
	EURO2	Diesel	42,367				
		Gasoline	54,233				
	EURO3	Diesel	51,932				
EURO3/EURO4	Gasoline	45,926					

Table 11: Coefficient $\omega_{20^{\circ}\text{C},20\text{km/h}}$ corresponding to excess emission at 20 °C and 20 km/h (in g), calculated from Table 8.

For example, for CO pollutant and Euro 2 gasoline cars:

- ✓ Using Table 11, $\omega_{20^{\circ}\text{C},20\text{km/h}}=8.012$
- ✓ Using Table 8, $f(T,V)=1.008+0.013\cdot T-0.014\cdot V$
- ✓ Using Table 10, $a(T)=0.071\cdot T-7.066$
- ✓ Using Table 9, $d_c(T,V)=1.997-0.099\cdot T-0.091\cdot V$

and therefore δ et $h(\delta)$ can be calculated, and finally:

$$\text{Excess Emission}_{\text{CO,Euro2,Gasoline}}(T, V, \delta) = \underbrace{8.012}_{\omega} \cdot \left[\underbrace{1.008 + 0.013 \cdot T - 0.014 \cdot V}_{f(T,V)} \right] \cdot \underbrace{\left(\frac{1 - e^{\frac{(0.071 \cdot T + 7.066) \cdot d}{1.997 + 0.099 \cdot T - 0.091 \cdot V}}}{1 - e^{(0.071 \cdot T + 7.066)}} \right)}_{h(d,T,V)}$$

A comparison can be made between the temperature and speed influences on excess emission. An example of influence of temperature decrease by 30 °C (20 °C to -10 °C) and average speed increase by 30 km/h (20 km/h to 50 km/h) on the f function is shown in Table 12. The

joint influence of speed and temperature is ranging from 0 to 71, with an average of 11.5. Thus the influence of temperature and speed is very significant, temperature influence being higher than speed influence except for NO_x, pollutant where speed influence being higher than temperature influence.

The light duty vehicles (LDV) are not concerned by our data base. Therefore we could consider, if necessary, that LDV excess emissions should be the same as for passenger cars (PC) but it would be much better to build a LDV cold start model using LDV specific data base.

Pollutant	Standard Emission	Fuel Type	f(-10°C.20km/h)	f(20°C.20km/h)	f(20°C.50km/h)	$\frac{f(-10,20)}{f(20,50)}$
CO	EURO0 CAT.	Gasoline	37.0	1	0.7	53.8
	EURO0 W/O CAT.	Gasoline/Diesel	44.1	1	19.9	2.2
	EURO1	Diesel	0.5	1	0	-
		Gasoline	0.4	1	0.6	0.6
	EURO2	Diesel	3.4	1	0.1	32.9
		Gasoline	2.6	1	1.7	1.6
	EURO3	Diesel	1	1	0.4	2.8
EURO3/EURO4	Gasoline	7.4	1	0.8	9.7	
CO ₂	EURO0 CAT.	Gasoline	9.4	1	0.6	15.3
	EURO0 W/O CAT.	Gasoline/Diesel	10.9	1	4.2	2.6
	EURO1	Diesel	0.7	1	0.2	4.0
		Gasoline	0.7	1	0.6	1.2
	EURO2	Diesel	3.2	1	0.4	8.1
		Gasoline	0.6	1	0.6	1.0
	EURO3	Diesel	0	1	0.6	0
EURO3/EURO4	Gasoline	2.2	1	0.8	2.9	
FC	EURO0 CAT.	Gasoline	0	1	78.1	0
	EURO0 W/O CAT.	Gasoline/Diesel	2.8	1	1.1	2.5
	EURO1	Diesel	0	1	0.1	0
		Gasoline	0	1	0.9	0
	EURO2	Diesel	23.7	1	0.3	70.8
		Gasoline	2.6	1	0.5	5.2
	EURO3	Diesel	0	1	0.6	0
EURO3/EURO4	Gasoline	2.1	1	0.2	10.5	
HC	EURO0 CAT.	Gasoline	18.7	1	0.8	22.7
	EURO0 W/O CAT.	Gasoline/Diesel	291	1	54.6	5.3
	EURO1	Diesel	0.3	1	0	-
		Gasoline	0.1	1	0.2	0.6
	EURO2	Diesel	12.5	1	0.4	31.1
		Gasoline	1.1	1	0.4	3.0
	EURO3	Diesel	4.8	1	0.6	7.6
EURO3/EURO4	Gasoline	18.3	1	1.3	13.7	
NO _x	EURO0 CAT.	Gasoline	24.1	1	0.8	30.8
	EURO0 W/O CAT.	Gasoline/Diesel	0	1	5.7	0
	EURO1	Diesel	0	1	2.0	0
		Gasoline	0.1	1	0.5	0.1
	EURO2	Diesel	0	1	0	-
		Gasoline	0.2	1	0.8	0.2
	EURO3	Diesel	0	1	3.8	0
EURO3/EURO4	Gasoline	0.8	1	0.7	1.1	

Table 12: Influence of temperature and speed on the speed and temperature function $f(T,V)$: comparison of 3 cases.

3. Conclusion

This modelling of excess emission under cold start conditions for passenger cars results from data provided by various European research organisations as part of MEET and Artemis projects. The present model takes into account mean speed, ambient temperature and travelled distance. This model results from measurements made over 4 driving cycles. Average speeds of these cycles range from 18.7 km/h to 41.5 km/h and temperature measurements range from -20 °C to 28 °C.

The cold excess emission is obtained in grams and is valid for gasoline and diesel cars, from Euro 0 to Euro 4 emission standard. This emission is given for a prescribed pollutant and vehicle technology. The general formula is written in the form of a reference excess emission multiplied by functions depending on average speed, engine temperature and travelled distance. For fuel consumption, it was determined using the carbon balance method. The forms of speed-temperature functions were assumed to be 3D-linear. For travelled distance, we assumed that its influence was in the shape of an exponential function (with a temperature influence) for all pollutants in order to simplify the model, even if the shape seems more complicated for NO_x pollutant. We also assumed that the trips were started with a cold engine, i.e. start engine temperature corresponding to ambient temperature. For intermediate start temperature conditions, we made the hypothesis that the excess emission corresponds to the cold start emission with the same start temperature: e.g. a start at an engine temperature of 30 °C corresponds to a cold start at an ambient temperature of 30 °C.

This model can be applied at different geographic scales: at a macroscopic scale (national inventories) using road traffic indicators and temperature statistics, or at a microscopic scale for a vehicle and a trip. If a model user could not access to necessary statistics, it would be recommended to integrate the statistics recorded at national level into the model, in order to further the model use and obtain a national average excess emission directly.

This study corresponds to the state-of-the-art at the present time. In the future, this model could be improved by different ways:

- updating this model using new data when available, either for the most recent passenger cars, or the light duty vehicles, or the heavy duty vehicles.
- it would be much more precise to have crossed distributions for different speeds and ambient temperatures.
- the number of analysed data has to be increased, especially for different speeds and low or high temperatures.
- intermediate engine temperatures must be considered, i.e. when engine start temperature does not correspond to ambient temperature (“cool starts”). It would be interesting to model start engine temperature as a function of ambient temperature, parking duration and maybe introduce an engine cooling coefficient.

Annex 1: Laboratory acronyms, addresses and persons to contact

Lab name	Signification	Contact person	Address	E-Mail (or phone and fax number)
EMPA	Eidgenössische Materialprüfungs- und Forschungsanstalt	M. Weilenmann	Überlandstrasse 129, 8600 Dübendorf, Switzerland	martin.weilenmann@empa.ch
IM CNR	Istituto Motori National Research Council	M. Rapone	viale Marconi 8 80125 Napoli, Italy	mrap@motori.im.na.cnr.it
INFRAS AG	Infrastruktur-, Umwelt- und Wirtschaftsberatung	M. Keller	Mühlemattstrasse 45 CH-3007 Bern Switzerland	mario.keller@infras.ch
INRETS	Institut National de Recherche sur les Transports et leur Sécurité	R. Joumard	Case 24 F-69675 Bron Cedex France	joumard@inrets.fr
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TNO	Netherlands org. for applied scientific research	R. Vermeulen	P.O. Box 6033 2600 JA Delft The Netherlands	vermeulen@wt.tno.nl
TRL	Transport Research Laboratory	I. MacCrae	Old Wokingham road Crowthorne Berkshire RG 45 6AU England	imccrae@trl.co.uk
TU-Graz	Graz University of Technology	S. Hausberger	Kopernikusgasse 24 A-8010 Graz Austria	hausberger@vkmb.tu-graz.ac.at
TÜV	TÜV Rheinland Sicherheit und Umweltschutz GmbH	D. Hassel	Konstantin Wille Strasse 1 D-51105 Köln Germany	+49-2218062479 +49-2218061756
VTI	Swedish National Road and Transport Research Institute	U. Hammarström	Statens väg- och transportforskningsinstitut S-581 95 Linköping Sweden	ulf.hammarstrom@vti.se
VTT	Technical Research Centre of Finland	J. Laurikko	Engine Technology P.O. Box 1601 FIN-02044 VTT Finland	juhani.laurikko@vtt.fi

Annex 2: Vehicles, data and temperature distribution

The next tables give the number of vehicles by pollutant, by laboratory, by category at the mean temperature of the vehicles measurements.

Cycle Name	Emission Standard	Fuel type	Mean Temperature	CO	CO ₂	FC	HC	NOx
ECE15-1	EURO0 CAT.	Gasoline	20	739	739		739	739
	EURO0 W/O CAT.	Gasoline	11	36	33	35	34	35
			19			46		
			20	251	233		243	253
	EURO1	Diesel	-7	3	3		3	3
		Gasoline	-7	36	36		36	36
EURO2	Gasoline	-7	26	26		26	26	
FTP72-1	EURO0 CAT.	Gasoline	15			10		
			20	727	727		727	727
	EURO0 W/O CAT.	Diesel	19	7				
			20		7	1	7	7
	EURO1	Gasoline	17	16	16	16	16	16
			19	2				
		Diesel	20		3	2	3	3
			15			3		
	EURO2	Gasoline	20	3	3		3	3
			20			13		
		Diesel	21	15	16		15	16
			16	5	5	5	5	5
	EURO3	Diesel	20			2		
			21	2	2		2	2
		Gasoline	22	10	10	10	10	10
IRC	EURO0 CAT.	Gasoline	16	10	10	10	10	10
	EURO0 W/O CAT.	Gasoline	11	8	8		8	8
			13			10		
			21	9			9	9
			22		8			
	EURO1	Diesel	21			2		
			22	2	3		3	3
	EURO2	Gasoline	16	4	4	4	4	4
			21			9		
		Diesel	22	13	16		17	17
			19	8	7	7		7
	EURO3	Gasoline	22				3	
			21			4		
			22	3	4		4	4
		Diesel	21			6		
			22	11	12		10	12

Cycle Name	Emission Standard	Fuel type	Mean Temperature	CO	CO ₂	FC	HC	NOx
IUFC	EURO0 CAT.	Gasoline	16		10	8		10
			17	9			9	
	EURO0 W/O CAT.	Gasoline	-20	6	6		6	6
			-7	6	6		6	6
			12	10	10		10	10
			13			11		
			23	7	7		7	7
	EURO1	Diesel	22	2	3	2	3	2
			16		4	4		4
		Gasoline	17	2			2	
	EURO2	Diesel	-20	6	6		6	6
			-7	6	6		6	6
			22	15	17	10	16	16
		Gasoline	-12	3	3	3	3	3
			21		12	12		
			23				8	9
	EURO3	Diesel	22	3	4	4	4	4
			-19	12	12		12	12
		Gasoline	-18			6		
			-8	11	11	6	11	11
			21	20	22			
	EURO4	Gasoline	22			15	18	19
			-19	2	2		2	2
			-18			2		
			-8	3	3	3	3	3
			21	2	2			
					2	2	2	

Table 13: Number of vehicles by cycle (defined in section 1.1), by pollutant, by category at the mean temperature of the vehicles measurements.

Cycle Name	Old EU EM STD	Fuel type	Mean Temperature	EMPA	INRETS	IM	TNO	VTT
ECE15-1	EURO0 CAT.	Gasoline	20				2956	
	EURO0 W/O CAT.	Gasoline	13		220			
			20		117		772	
			21		26			
			14		64			
	EURO1	Diesel	-7					12
Gasoline		-7					144	
EURO2	Gasoline	-7					104	
FTP72-1	EURO0 CAT.	Gasoline	15		10			
			20		40		2868	
	EURO0 W/O CAT.	Diesel	19		4		24	
			14		1			
		Gasoline	17	30	50			
			20		4			
	EURO1	Diesel	22		9			
			Gasoline	14		15		
	EURO2	Diesel	21	23	37			
			22	6	9			
		Gasoline	16		25			
			17		10			
EURO3	Diesel	22	30	20				
		Gasoline	22					
IRC	EURO0 CAT.	Gasoline	15		50			
	EURO0 W/O CAT.	Gasoline	13		9	1		
			17	24	39	4		
	EURO1	Diesel	21		9			
			18		4			
		Gasoline	17		15	5		
			22	18	37	4		
	EURO2	Diesel	23	6	6	1		
			Gasoline	19		21	8	
		Gasoline	22		1	2		
			22		9	10		
	EURO3	Diesel	22		4	2		
Gasoline			21		4	2		
		Gasoline	22	24	13	8		

Cycle Name	Old EU EM STD	Fuel type	Mean Temperature	EMPA	INRETS	IM	TNO	VTT
IUFC	EURO0 CAT.	Gasoline	16		37			
			17		9			
	EURO0 W/O CAT.	Gasoline	-20	24				
			-7	24				
			21	24	12	4		
			18		3	1		
			10		35			
	EURO1	Diesel	21		6			
			18		6			
		Gasoline	16		9	3		
			17		1	1		
	EURO2	Diesel	20		1	1		
			-20	24				
			-7	24				
			22	18	26	3		
		Gasoline	23	6	19	2		
			-20					5
			-8					10
			21		12	8		4
			23		5	8		4
			25			4		2
	EURO3	Diesel	22		8	8		
			23		1	2		
		Gasoline	-19	24				24
			-18					6
			-8	24				30
	EURO4	Gasoline	22	6	8	10		12
			23	18	3	15		18
			23					10

Table 14: Number of vehicles per cycle (defined in section 1.1), per laboratory, per category at the mean temperature of the vehicles measurements.

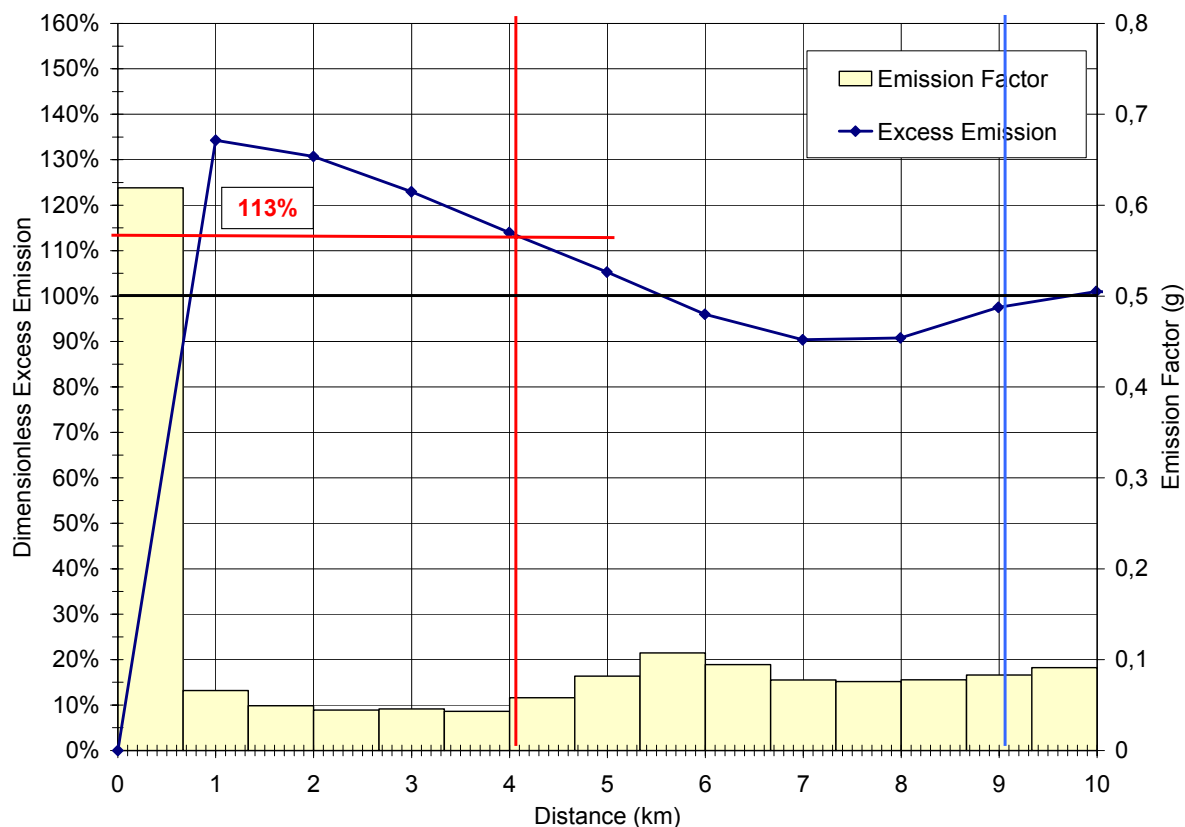
Laboratory	Cycle Name	Temperature	CO	CO ₂	FC	HC	NO _x	
EMPA	FTP72-1	Min	21,9	21,9	21,9	22,5	21,9	
		Max	23,4	23,4	23,4	23,4	23,4	
	IRC	Min	23,0	23,0		23,0	23,0	
		Max	23,0	23,0		23,0	23,0	
	IUFC	Min	-20,0	-20,0		-20,0	-20,0	
		Max	23,0	23,0		23,0	23,0	
INRETS	ECE15-1	Min	8,0	8,0	8,0	8,0	8,0	
		Max	27,0	27,0	27,0	27,0	27,0	
	FTP72-1	Min	9,0	9,0	9,0	9,0	9,0	
		Max	26,0	26,0	26,0	26,0	26,0	
	IRC	Min	6,0	6,0	6,0	6,0	6,0	
		Max	25,0	28,0	25,0	28,0	28,0	
	IUFC	Min	4,0	4,0	4,0	4,0	4,0	
		Max	27,0	28,0	28,0	27,0	27,0	
	ISTITUTO MOTORI	IRC	Min	23,0	23,0	23,0	23,0	23,0
			Max	25,0	25,0	25,0	25,0	25,0
IUFC		Min	23,5	23,5	23,5	23,5	23,5	
		Max	26,0	26,0	26,0	26,0	26,0	
TNO	ECE15-1	Min	20,0	20,0		20,0	20,0	
		Max	20,0	20,0		20,0	20,0	
	FTP72-1	Min	20,0	20,0		20,0	20,0	
		Max	20,0	20,0		20,0	20,0	
VTT	ECE15-1	Min	-7,0	-7,0		-7,0	-7,0	
		Max	-7,0	-7,0		-7,0	-7,0	
	IUFC	Min	-20,0	-20,0	-20,0	-20,0	-20,0	
		Max	23,7	23,7	23,7	23,7	23,7	

Table 15: Minimal and maximal temperatures of the vehicles measurements per laboratory, per cycle (defined in section 1.1), per pollutant.

Annex 3: Example of dimensionless excess emissions versus distance (km)

The figure below shows the cumulative dimensionless excess emission (ratio of absolute excess cold start emission to total absolute excess cold start emission) as a function of the distance (km) for short Inrets free-flow urban cycle (IUFC).

This graphic explains why sometimes the correction factor can be less than 1.

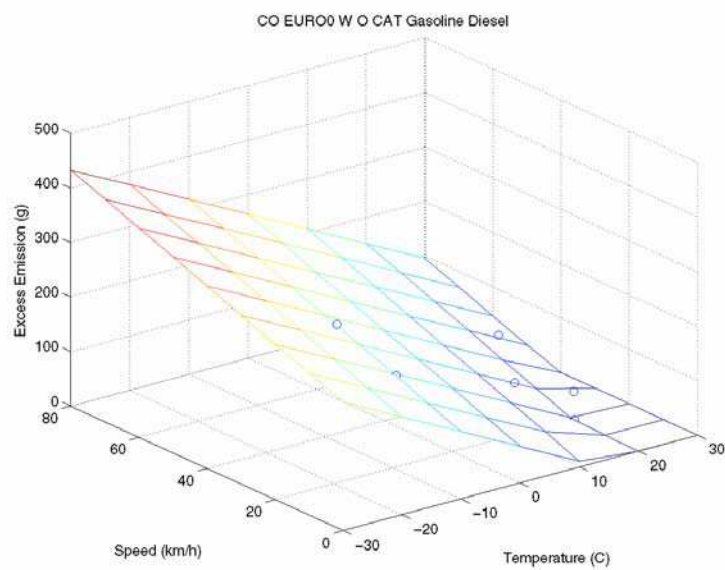
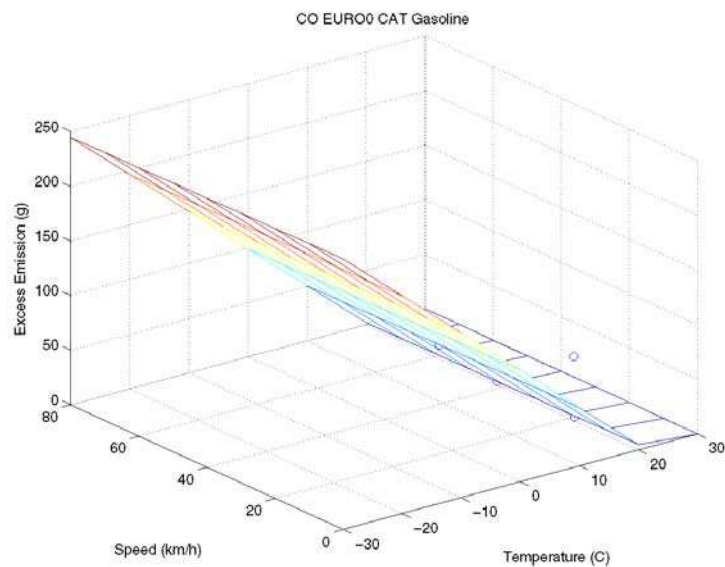


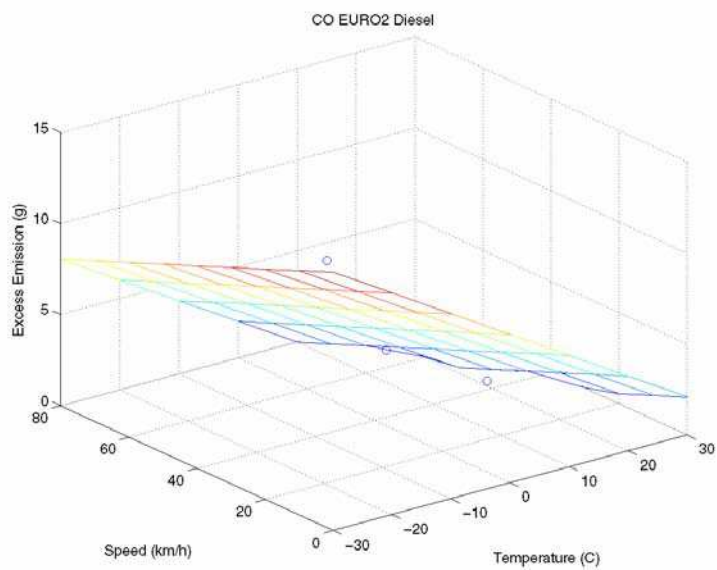
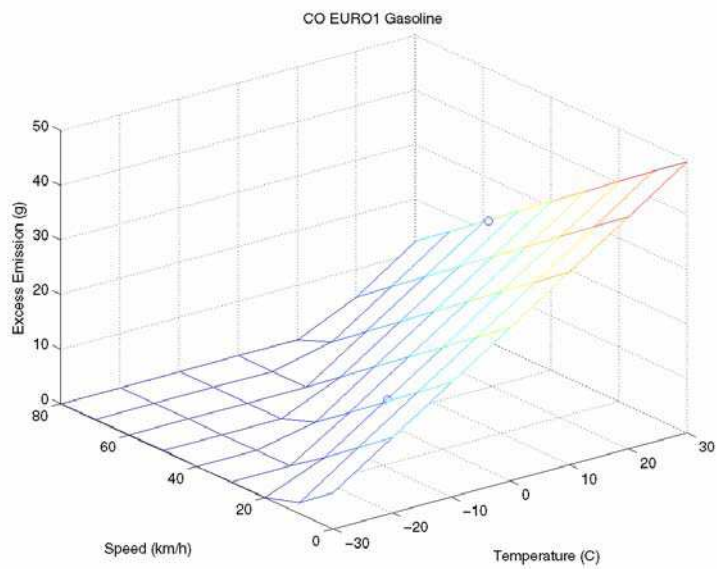
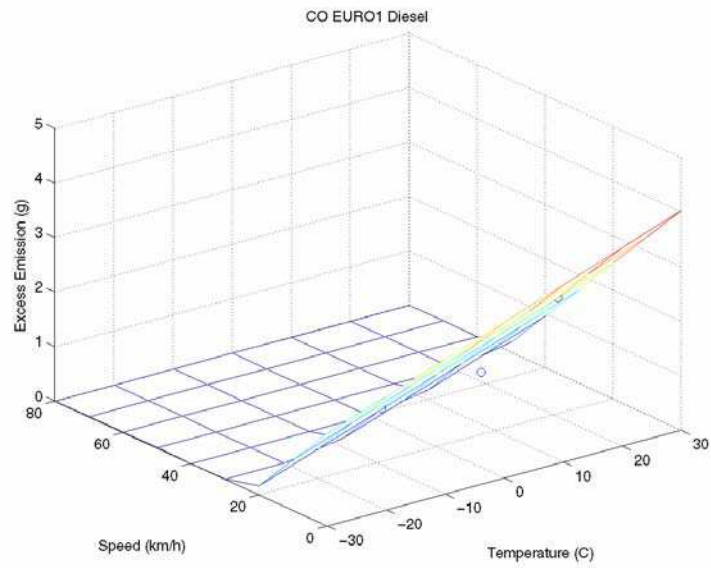
Correction calculation example of ECE-15 cycle for NOx pollutant on EURO3 Gasoline cars (at -19°C).

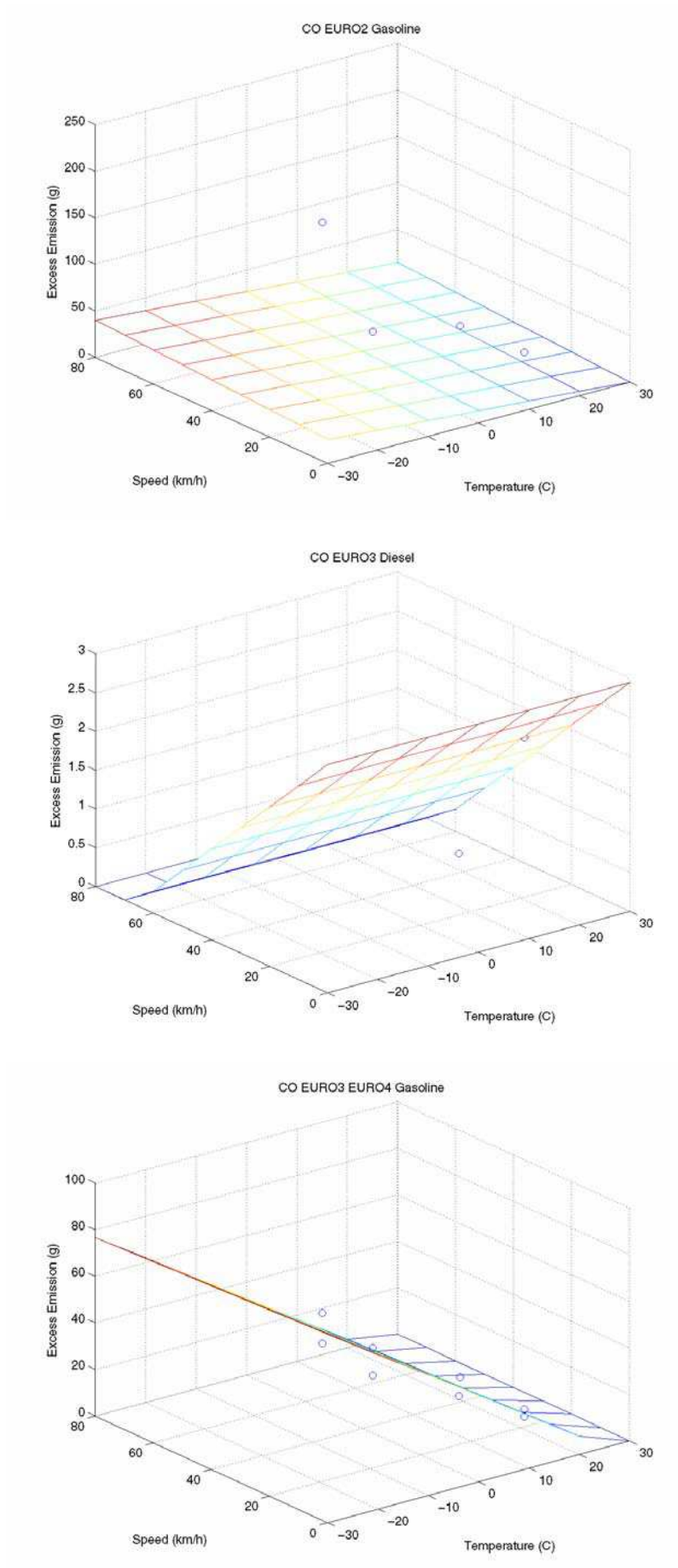
Annex 4: Excess emissions (g) versus vehicle speed (km/h) and ambient temperature (°C)

A point represents an average of the data for the category, the speed and the temperature, and the plan is the regression curve (linear regression) associated to those data.

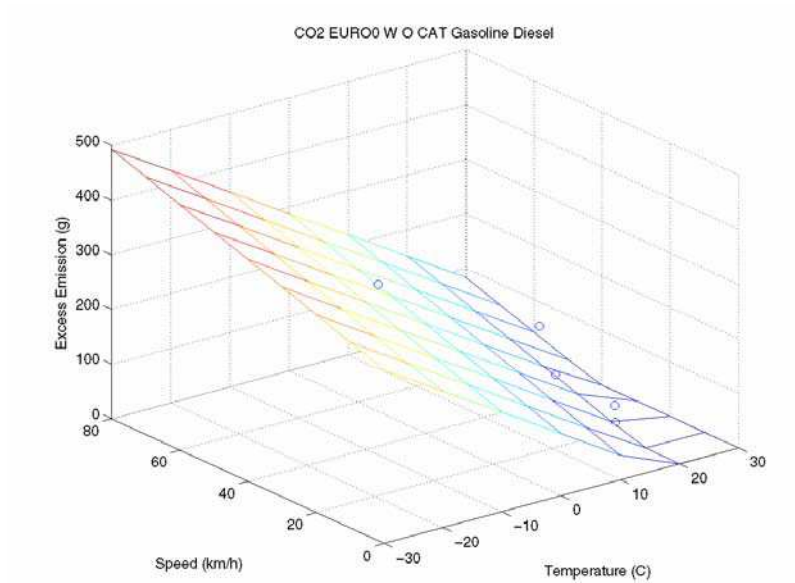
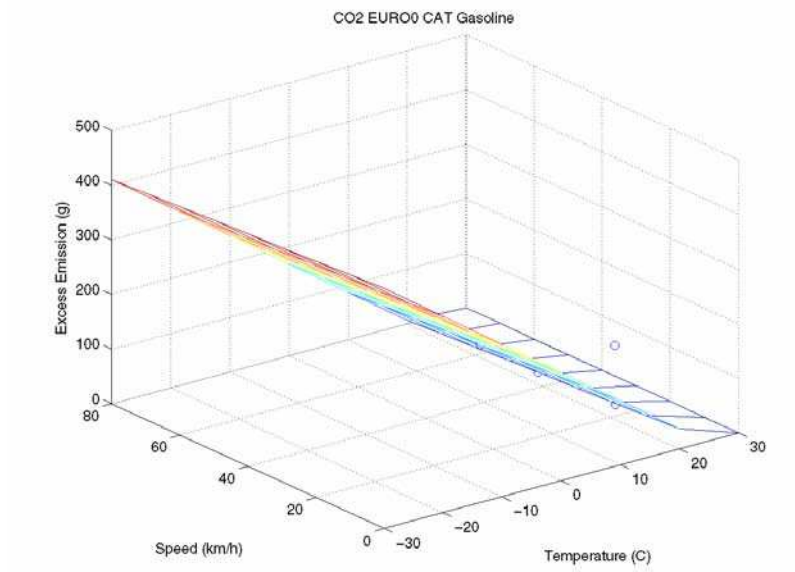
Annex 4.1: CO

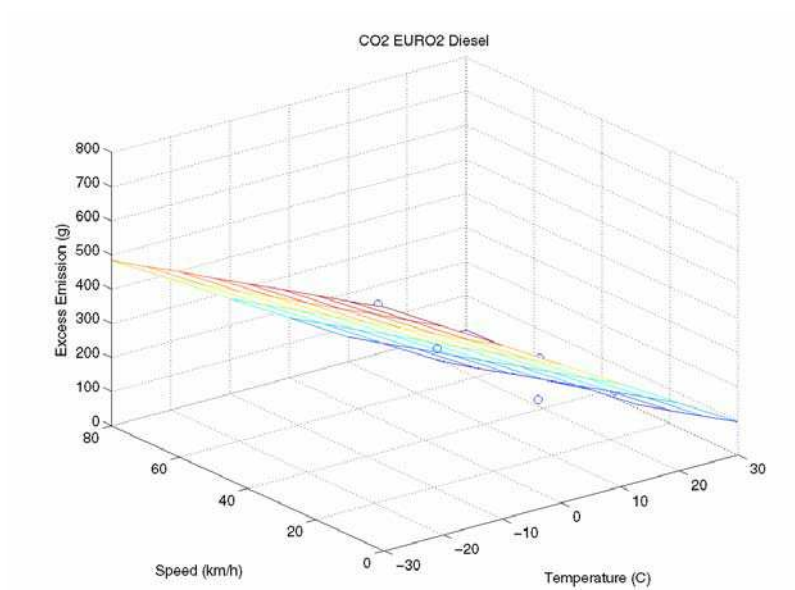
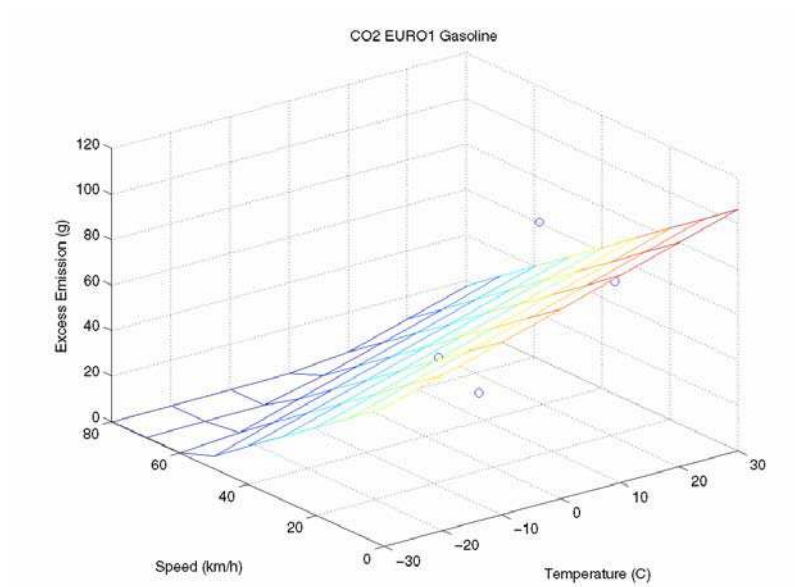
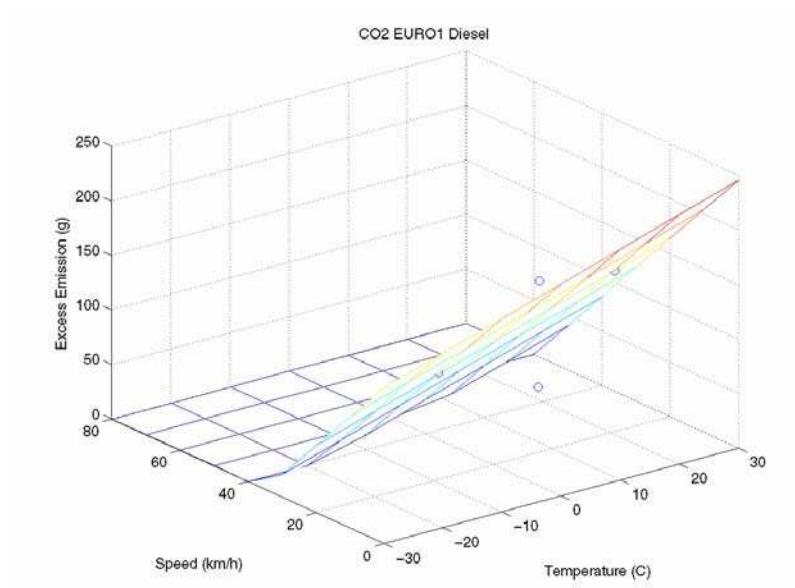


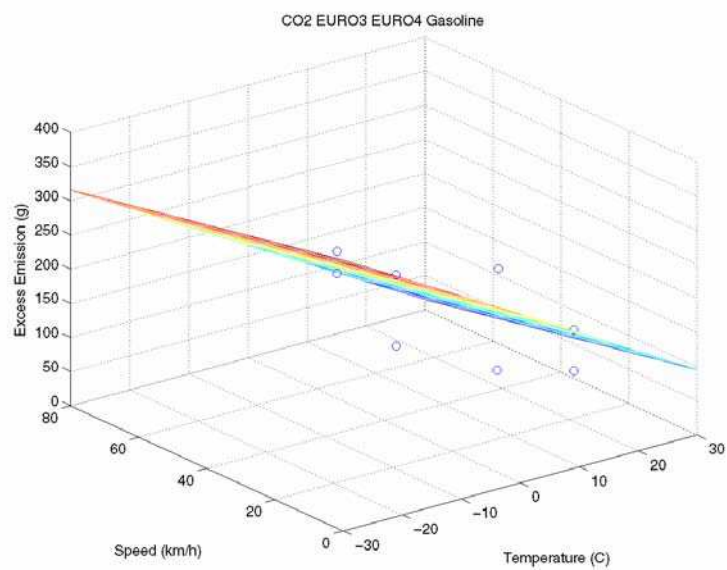
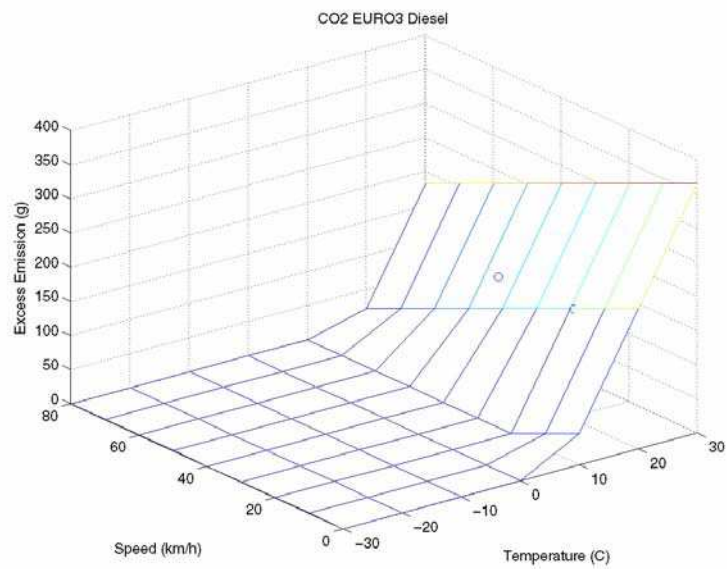
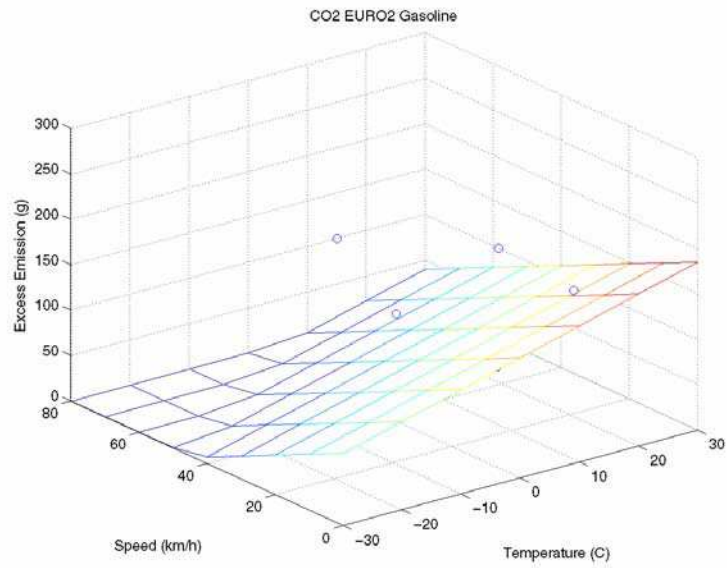




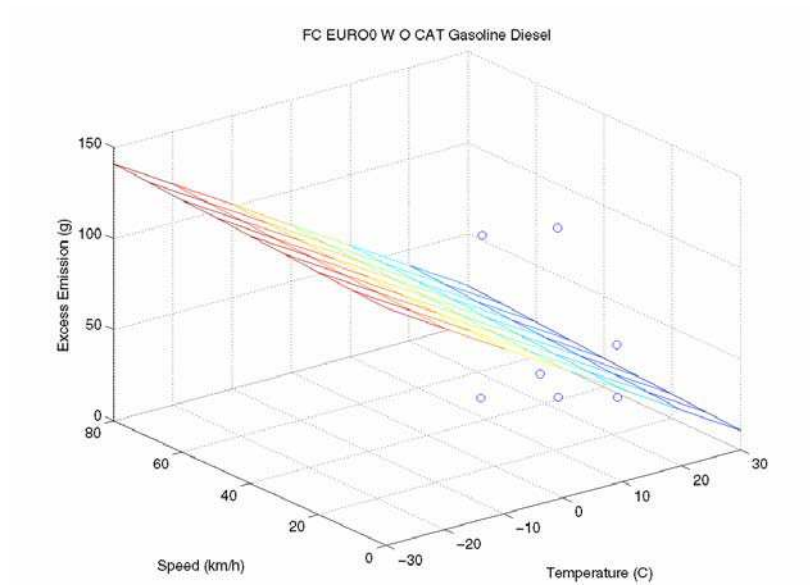
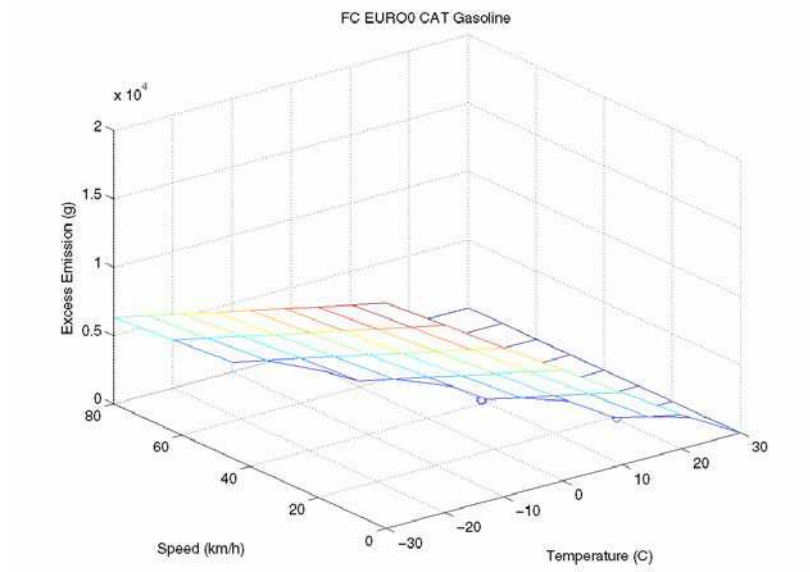
Annex 4.2: CO₂

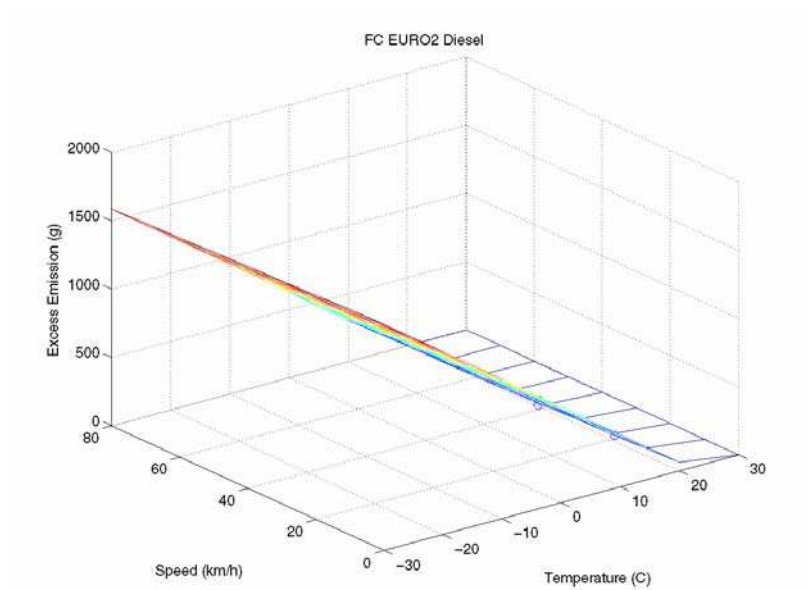
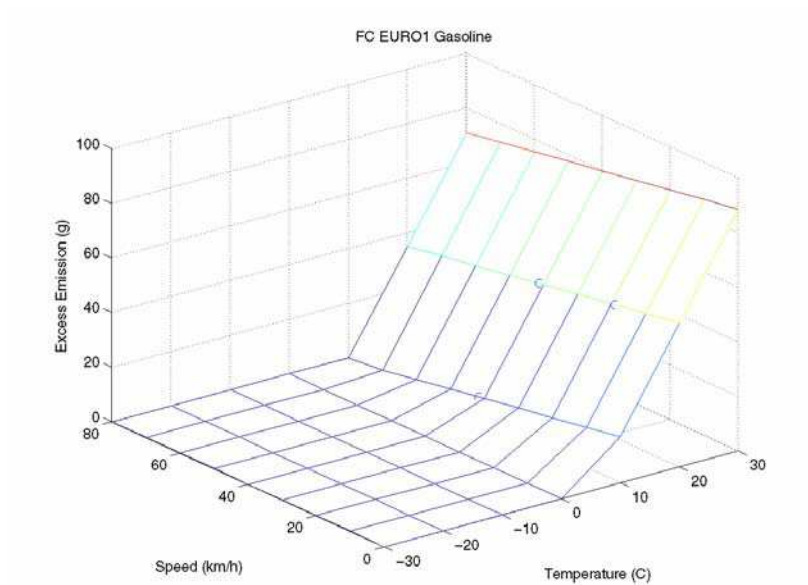
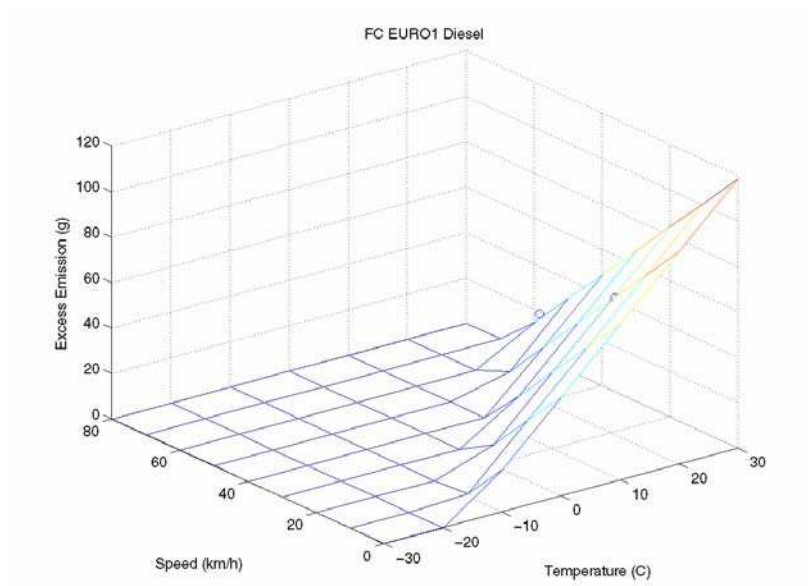


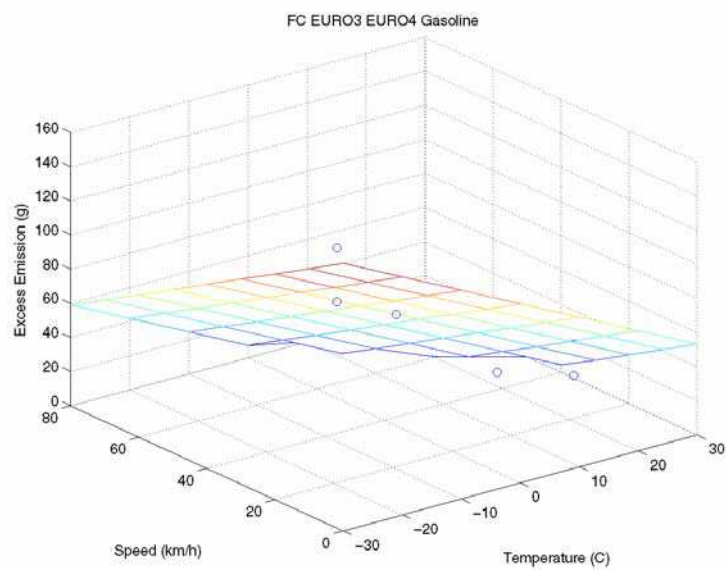
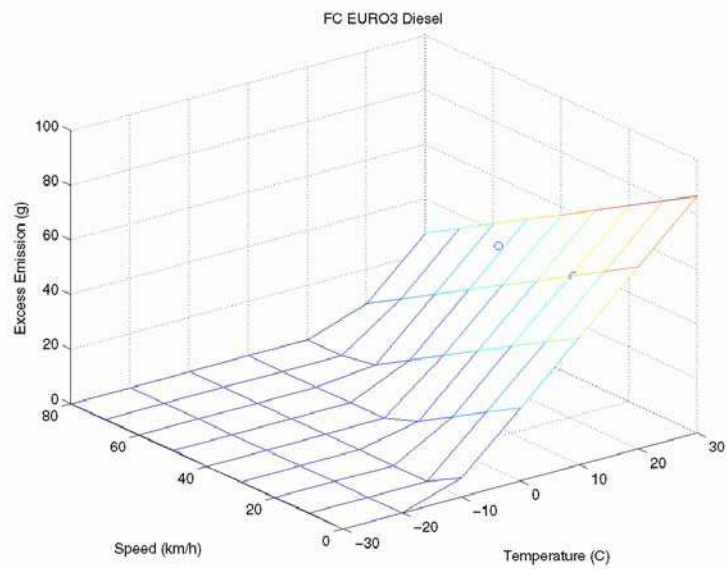
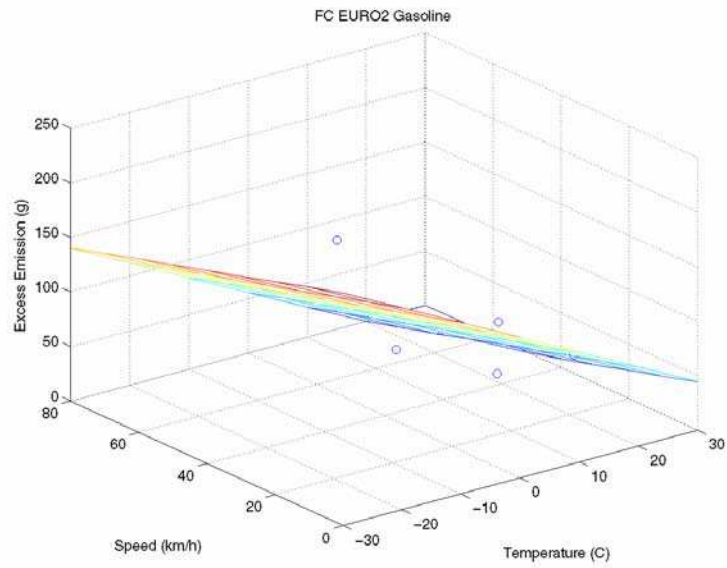




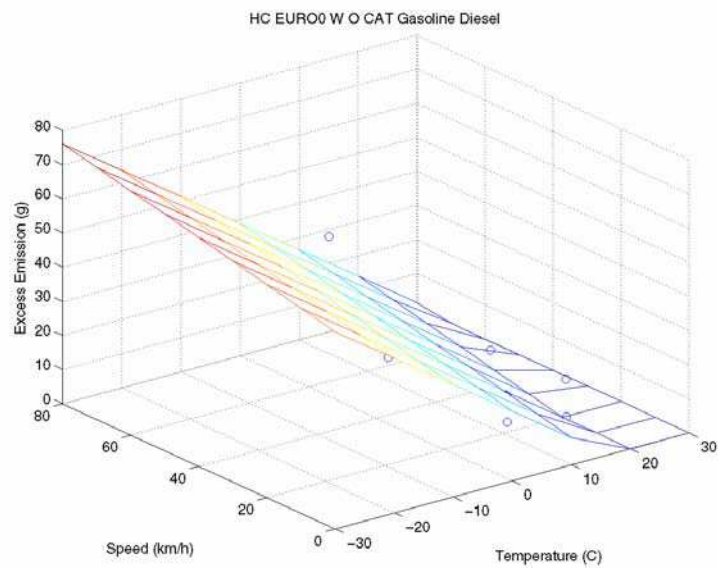
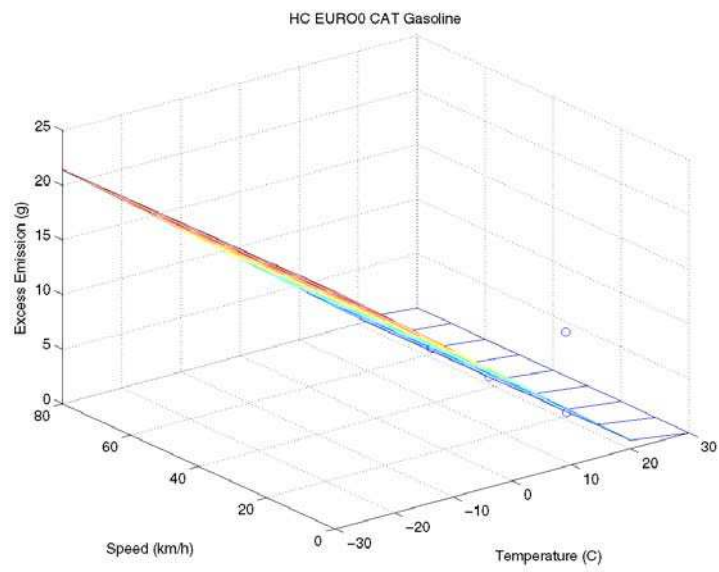
Annex 4.3: FC

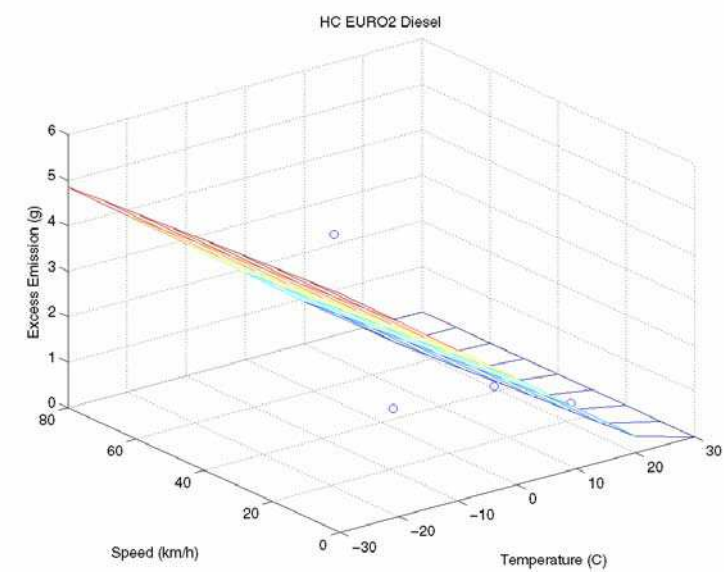
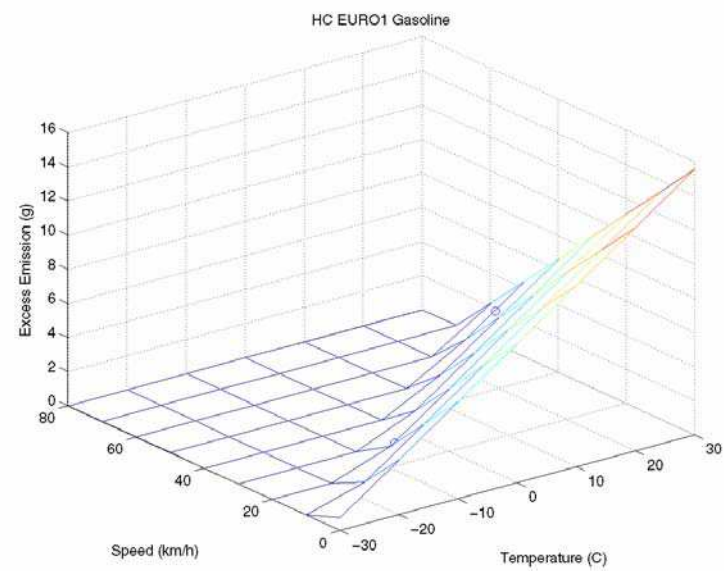
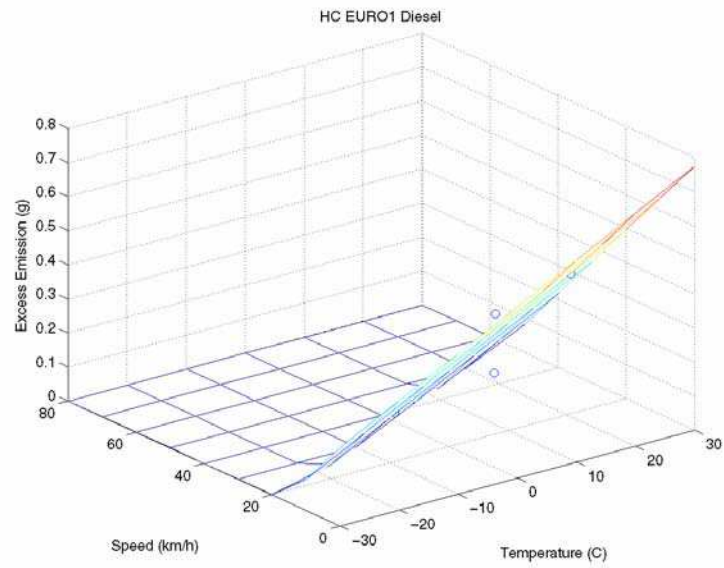


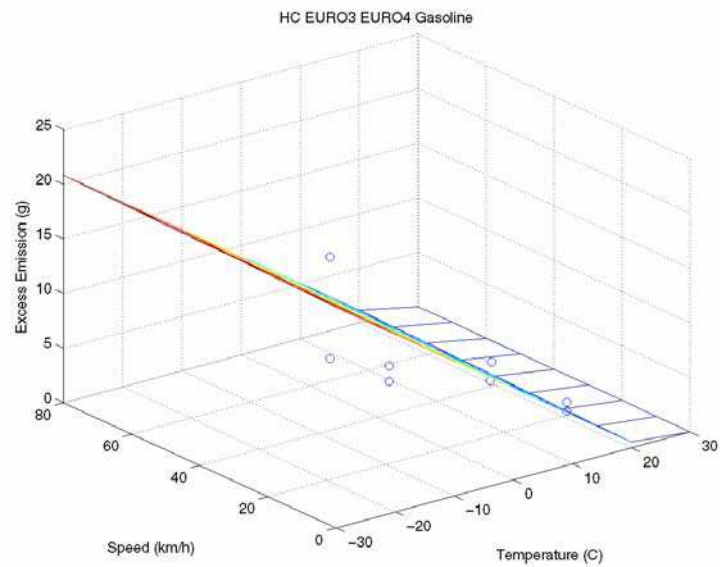
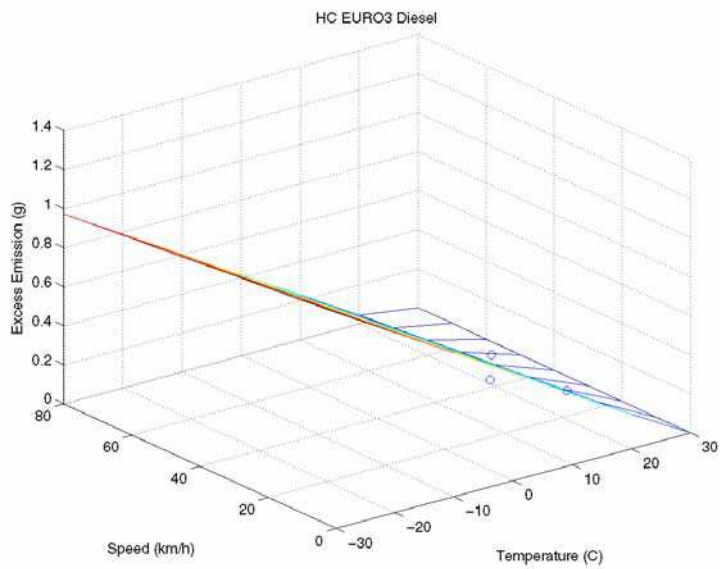
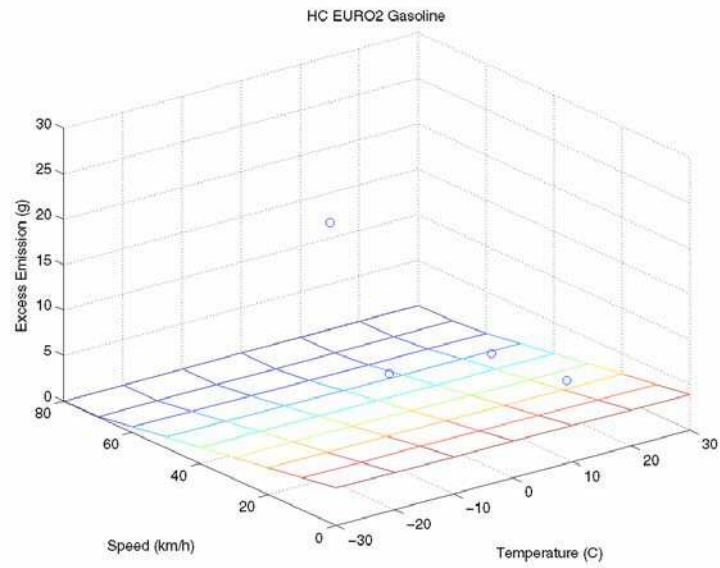




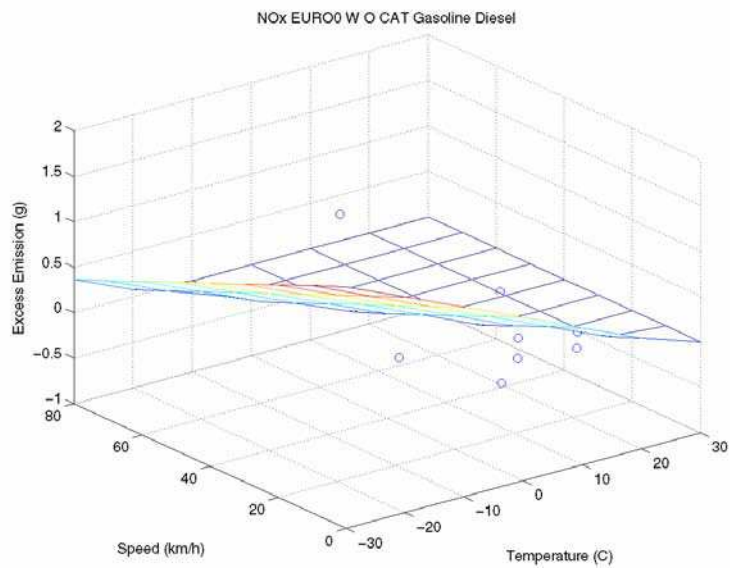
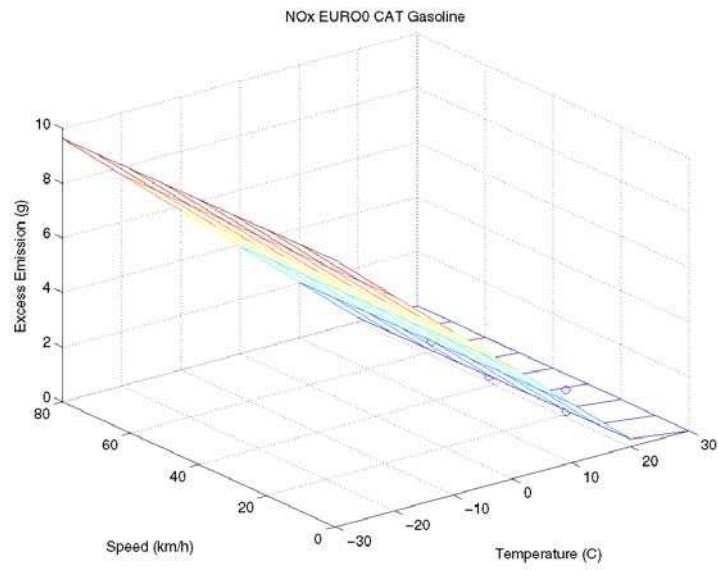
Annex 4.4: HC

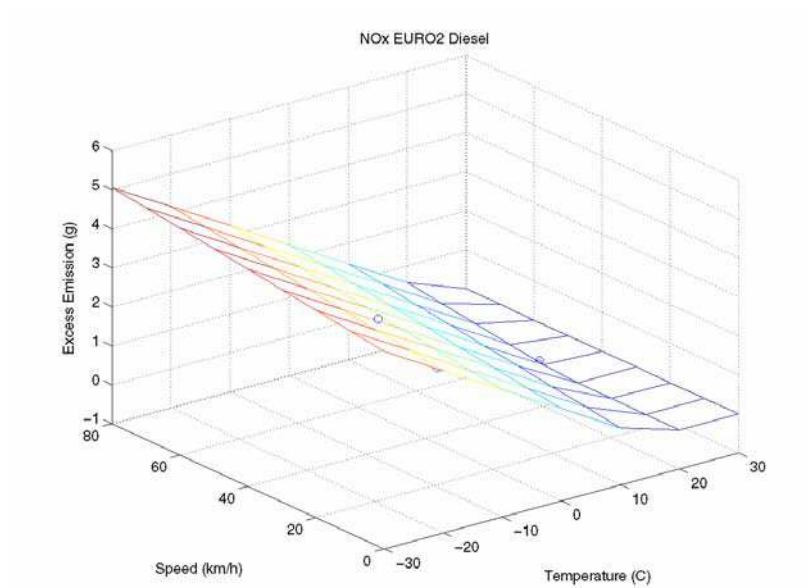
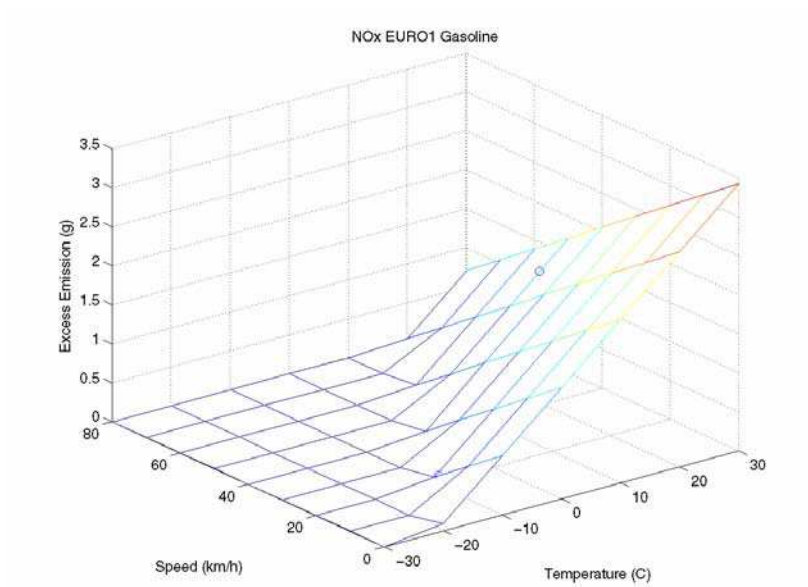
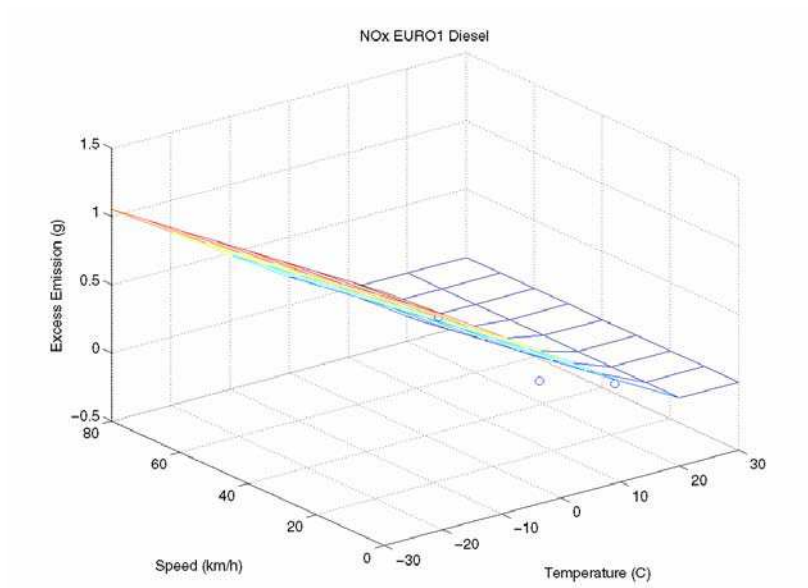


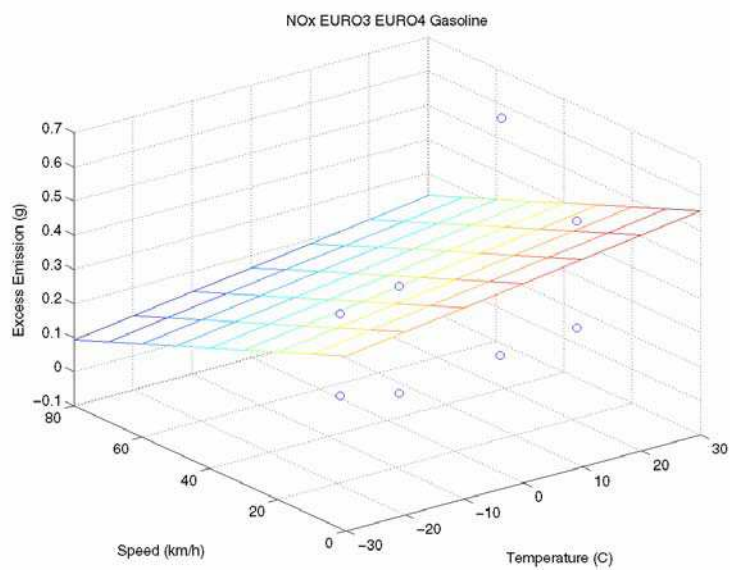
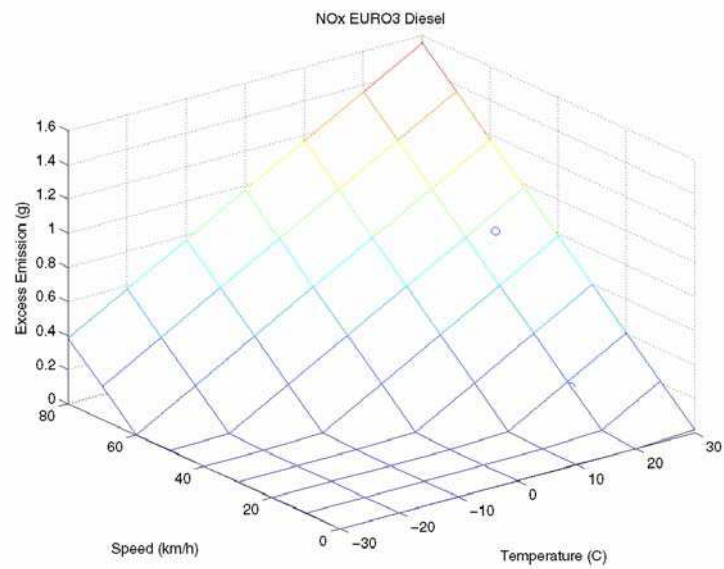
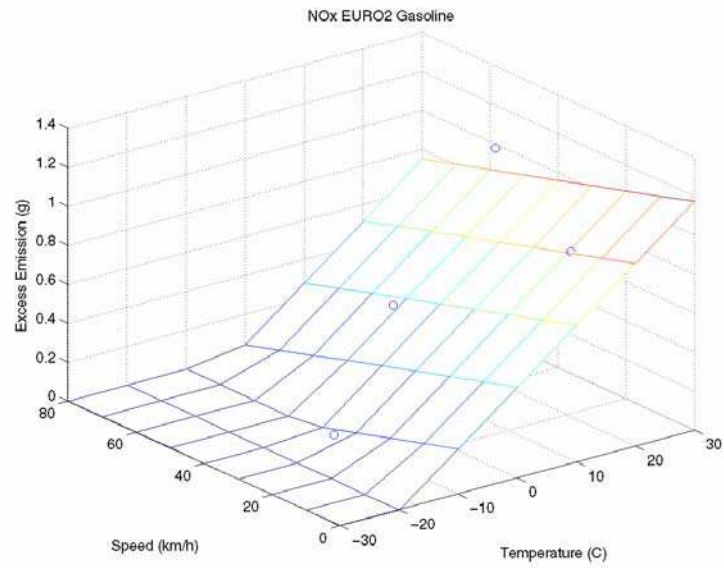




Annex 4.5: NO_x

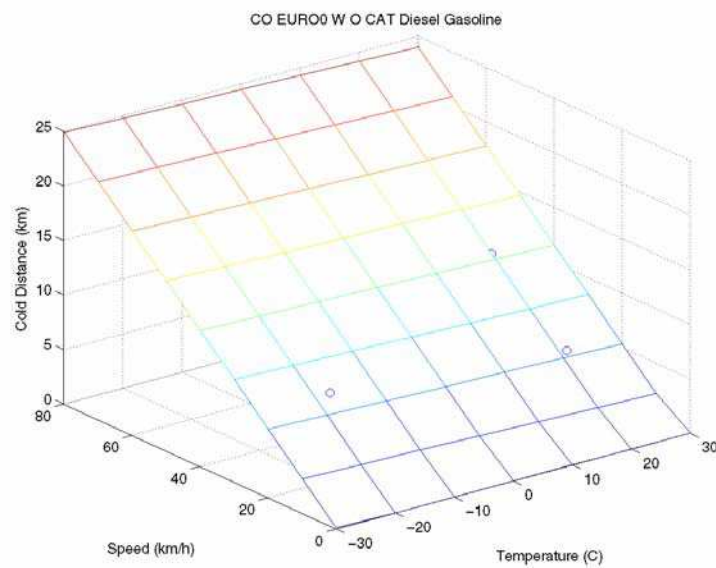
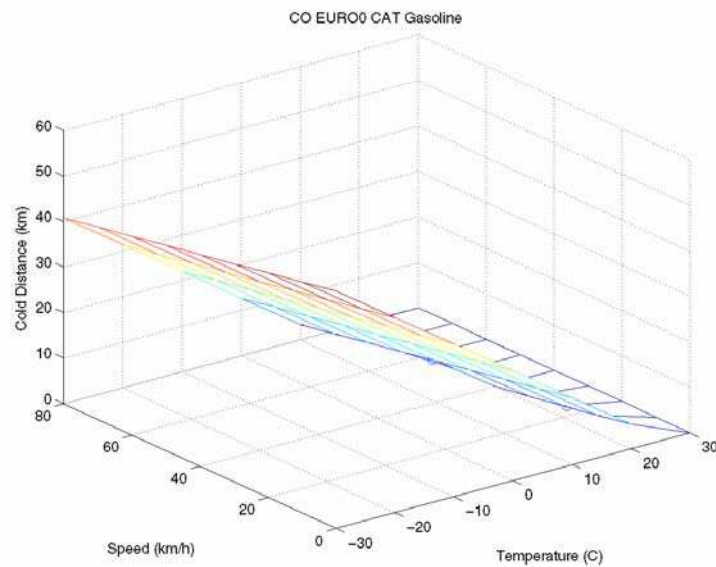


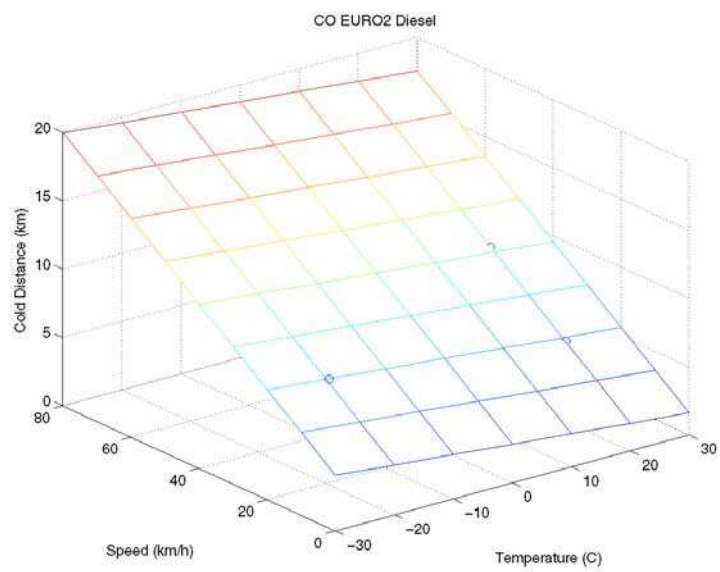
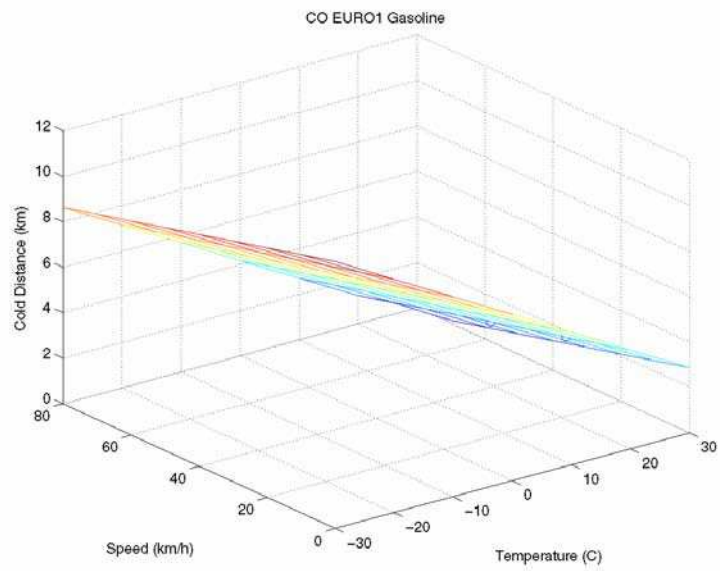
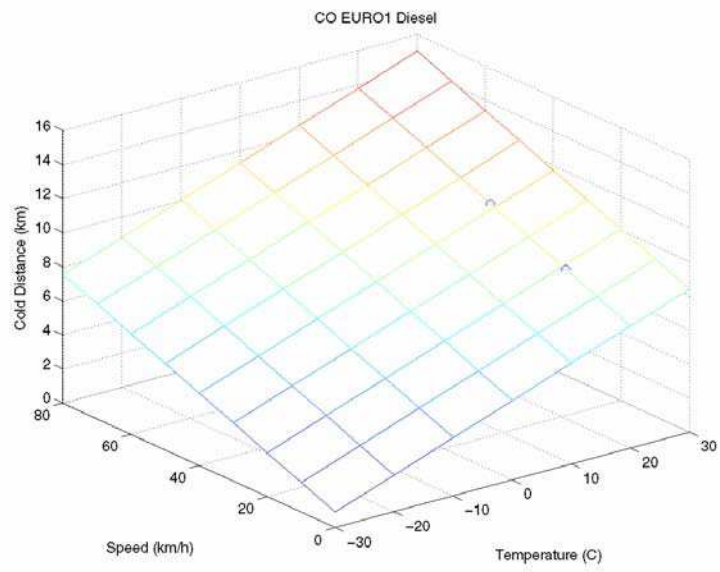


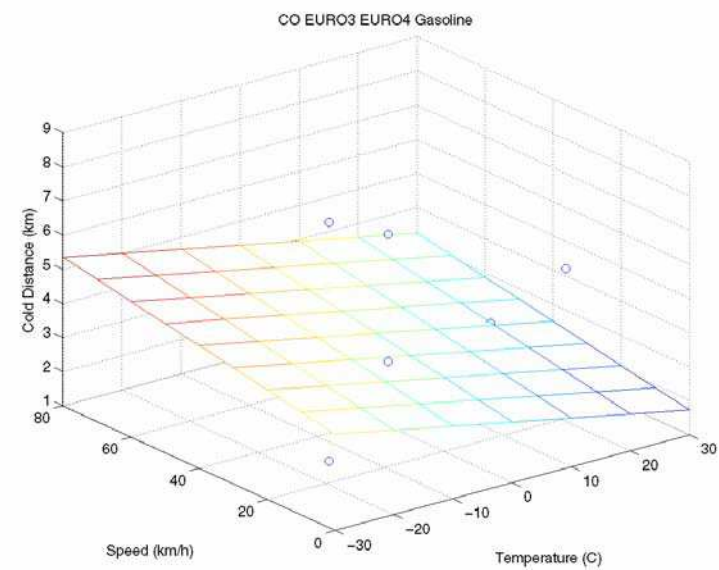
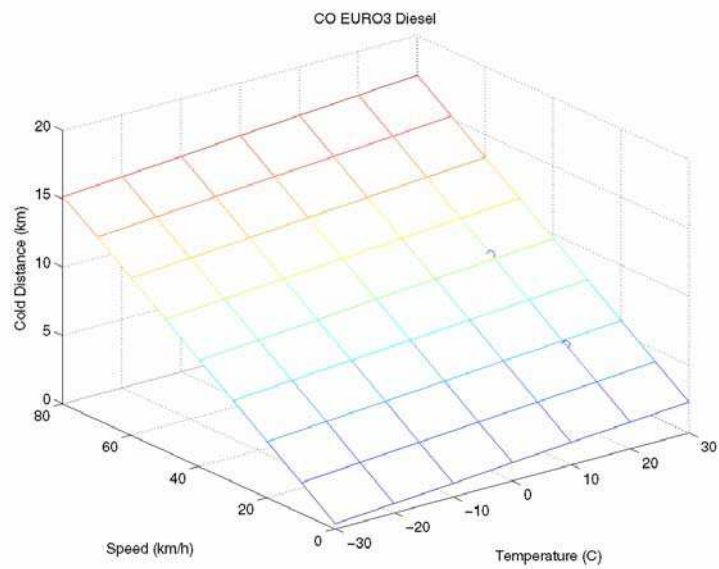
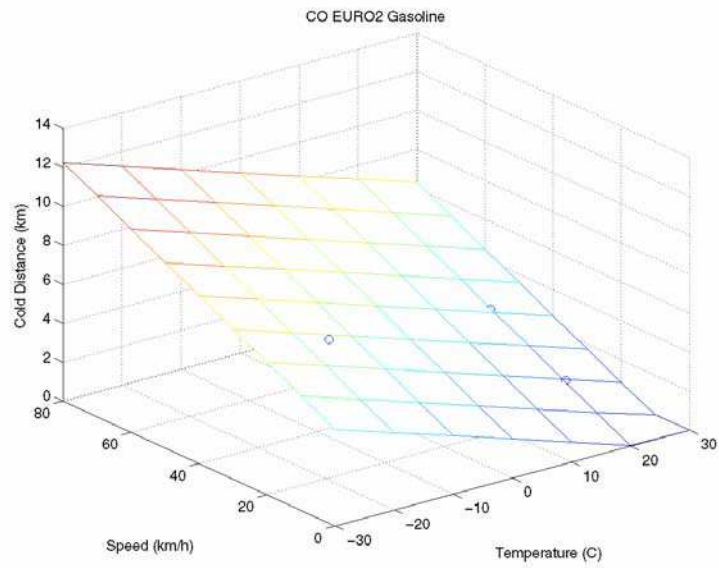


Annex 5: Cold distance (km) as function of the vehicle speed (km/h) and the temperature (°C).

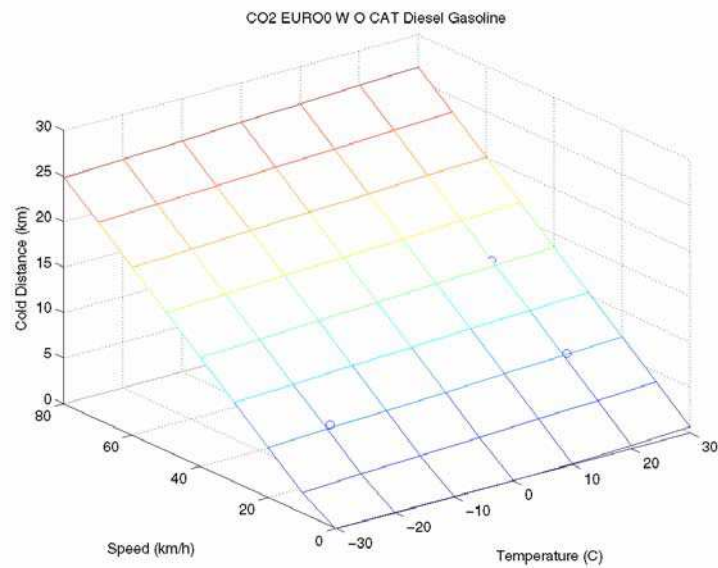
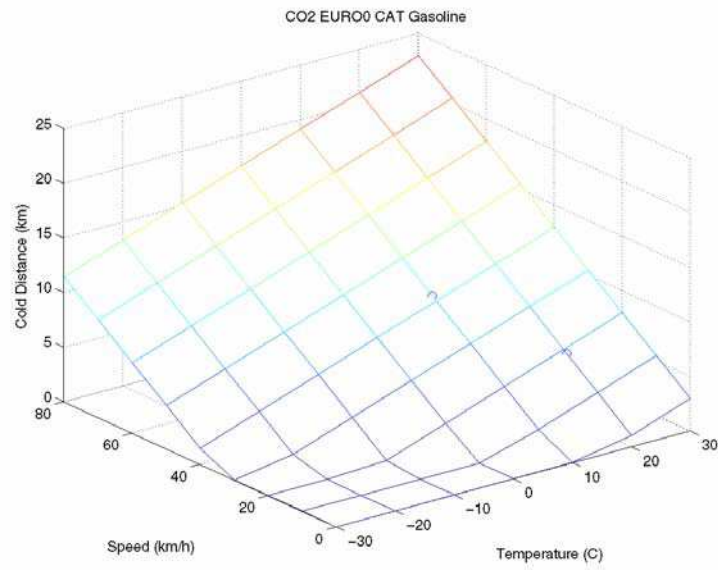
Annex 5.1: CO

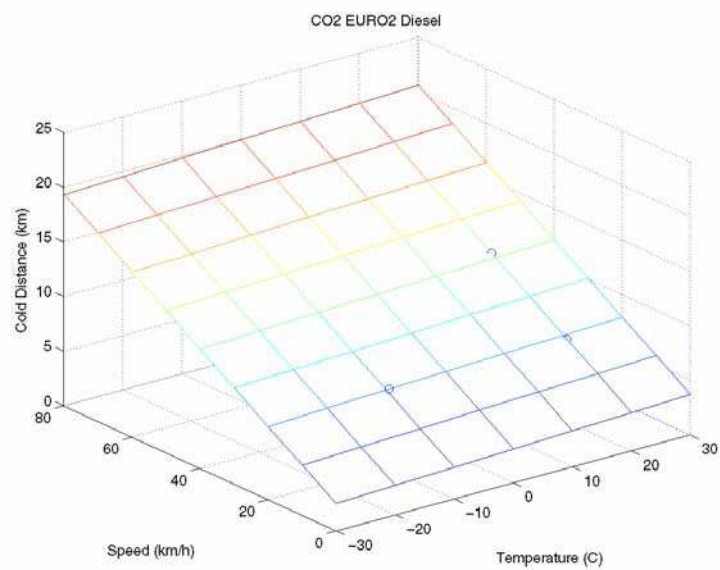
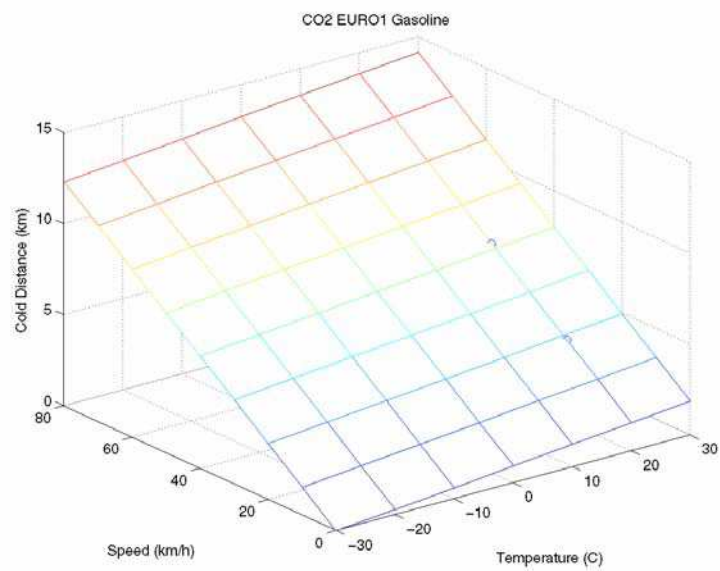
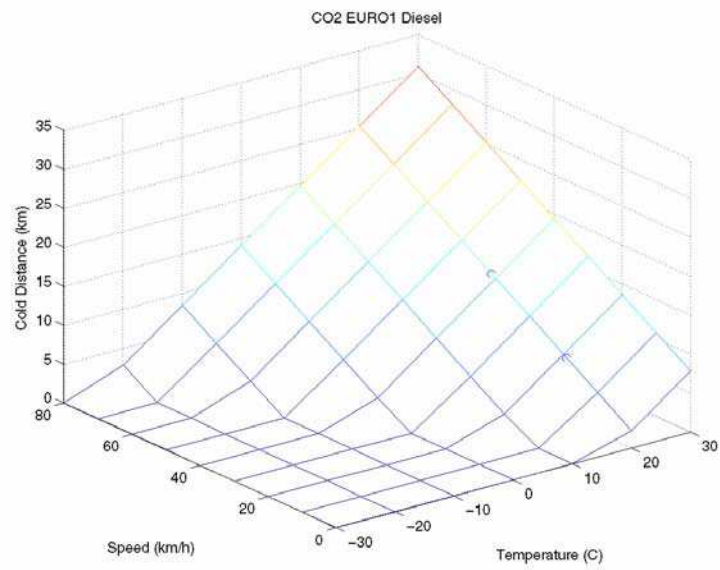


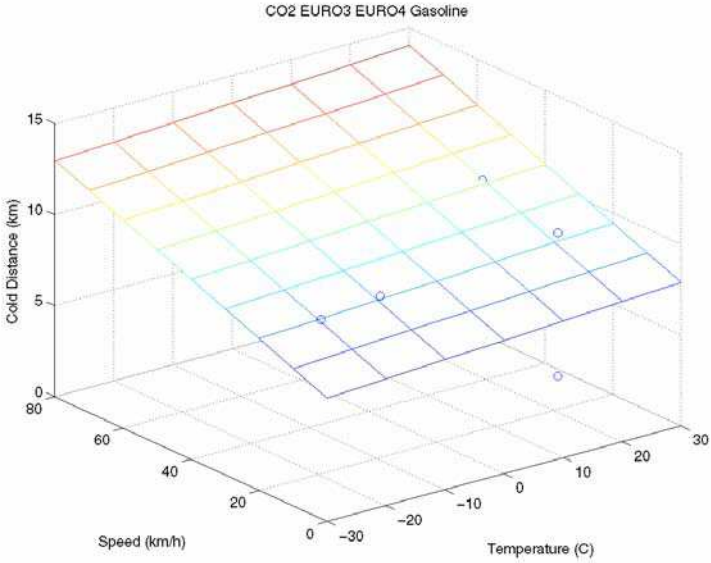
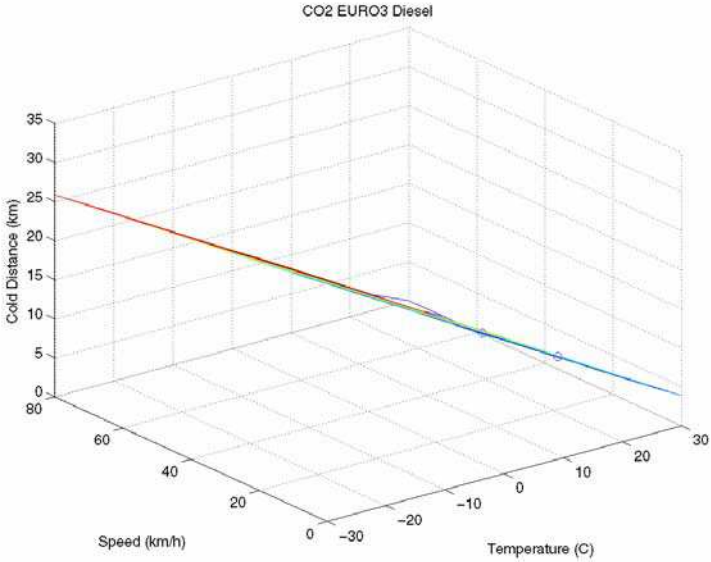
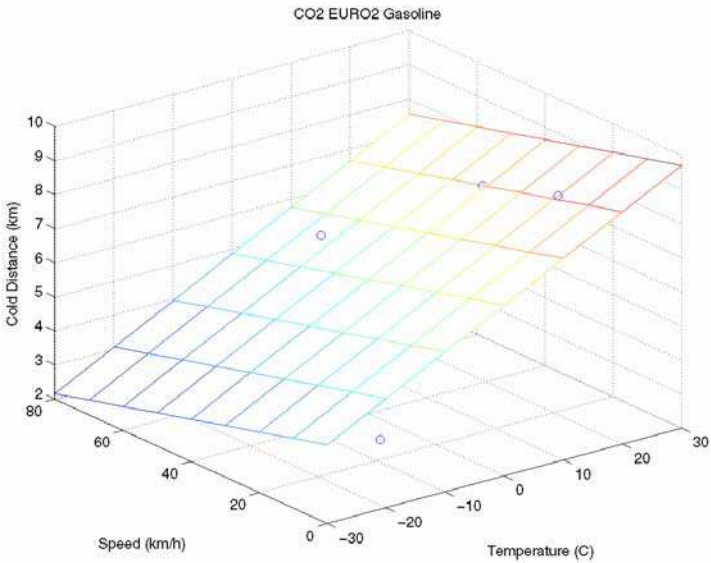




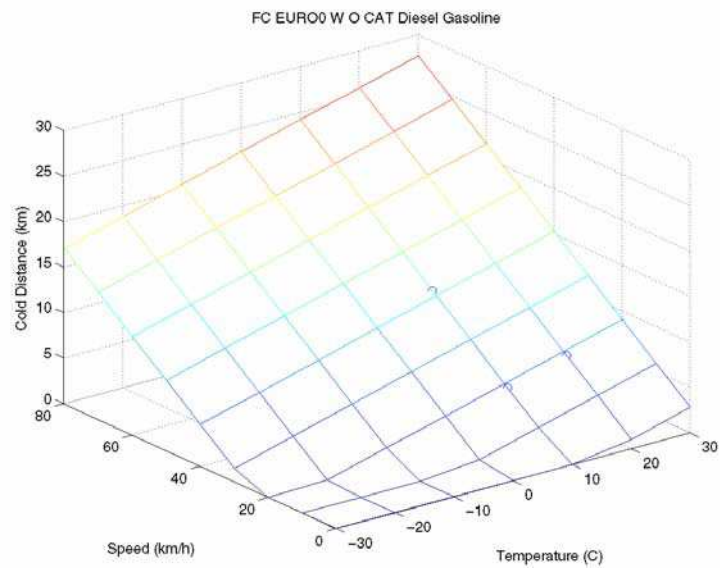
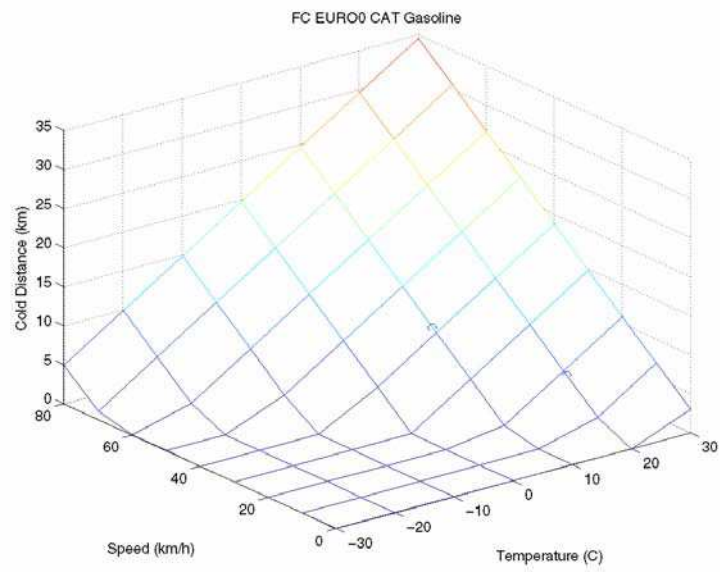
Annex 5.2: CO2

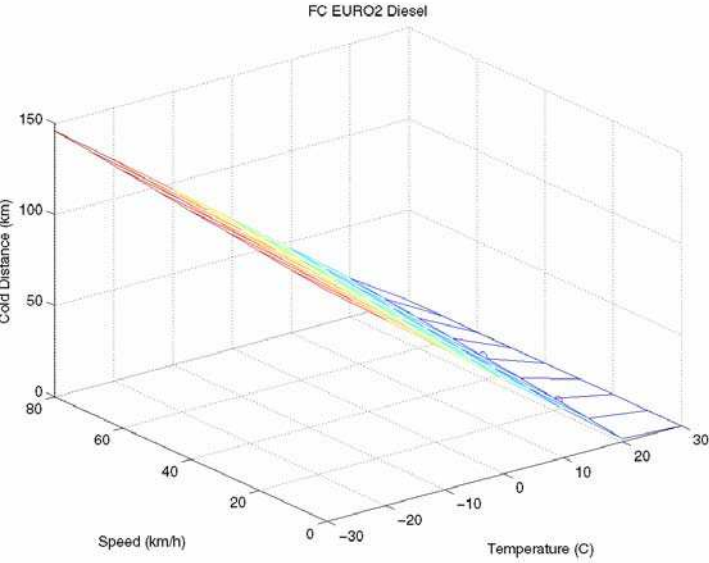
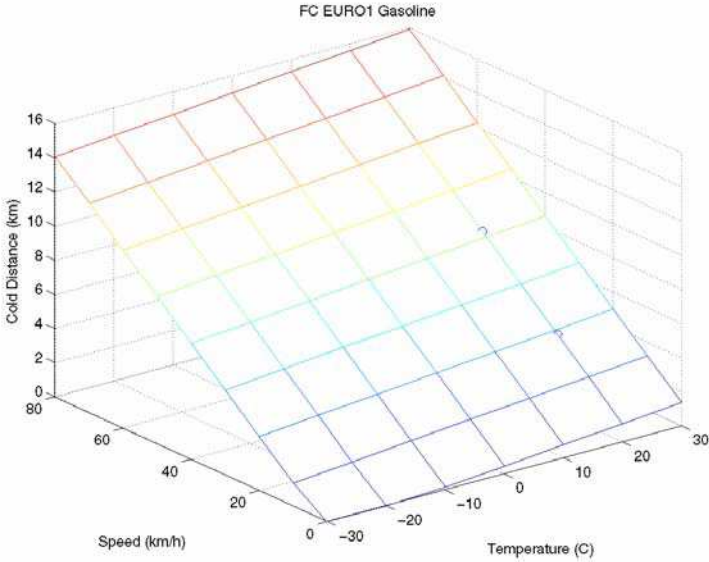
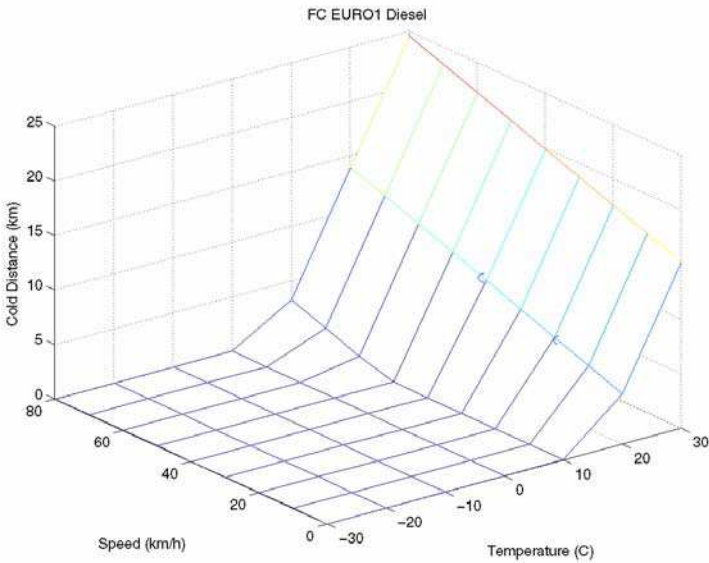


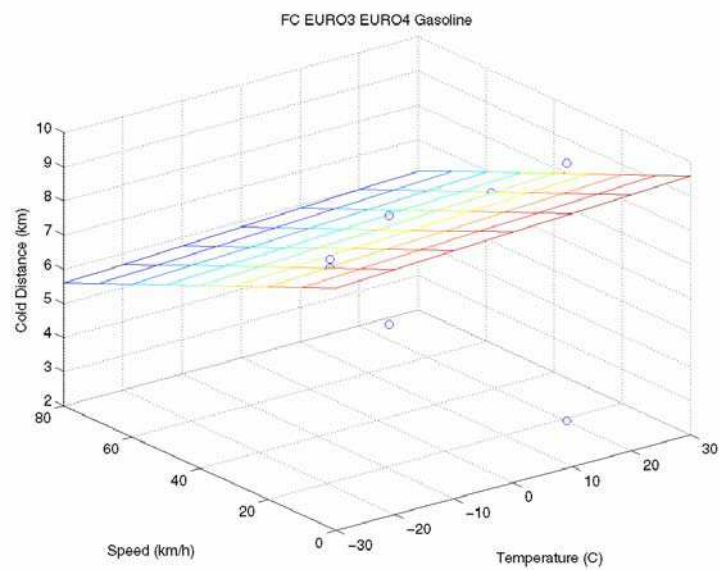
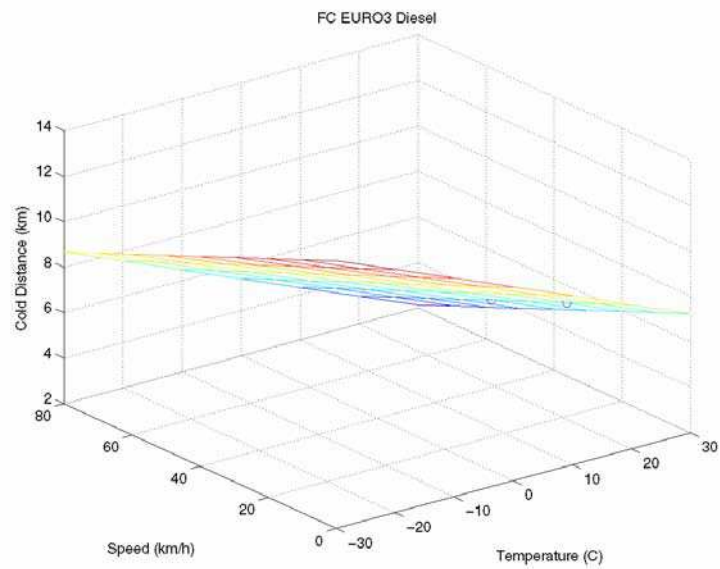
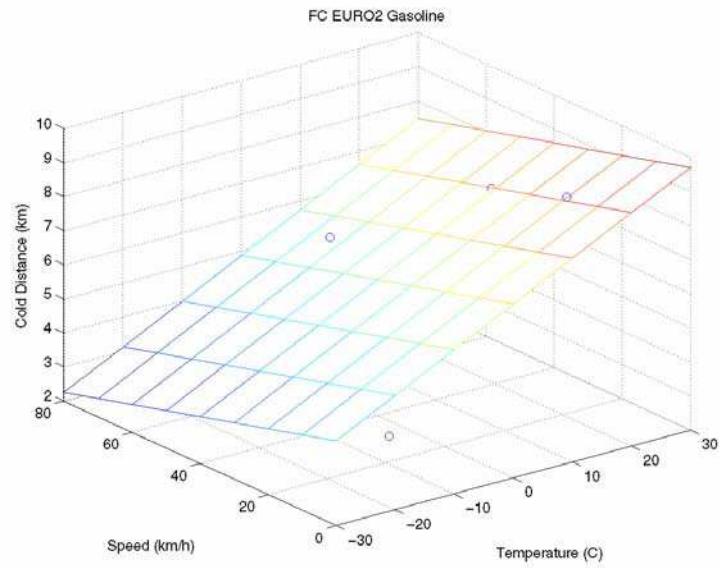




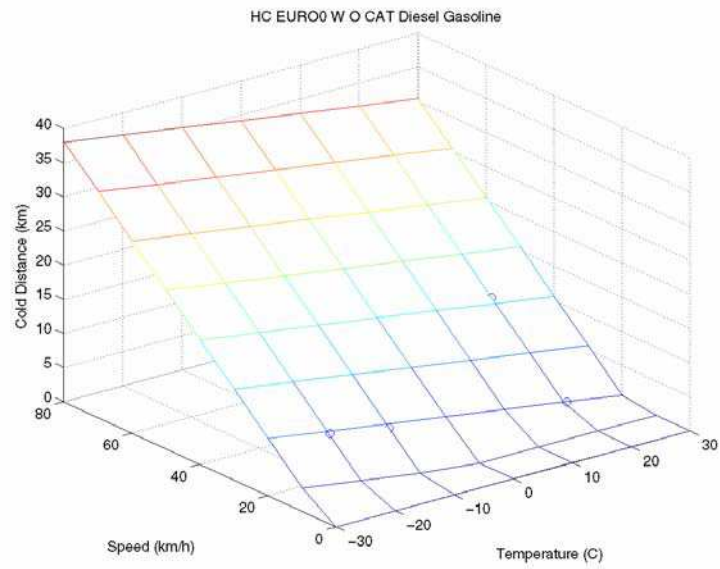
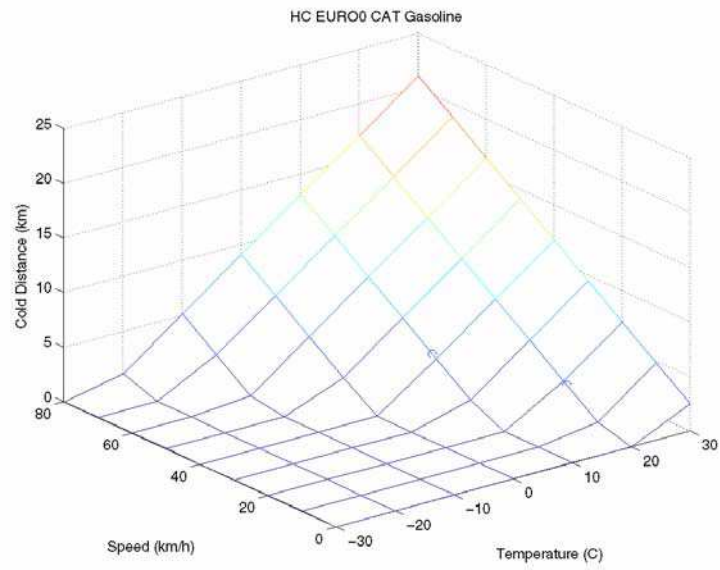
Annex 5.3: FC

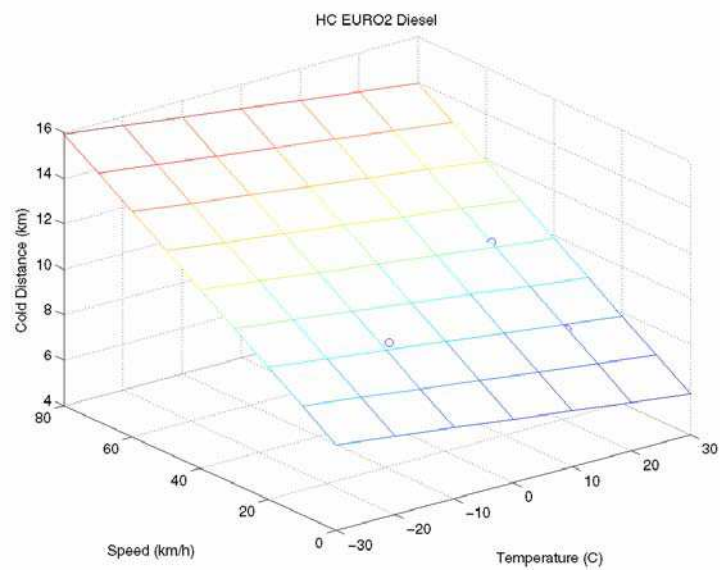
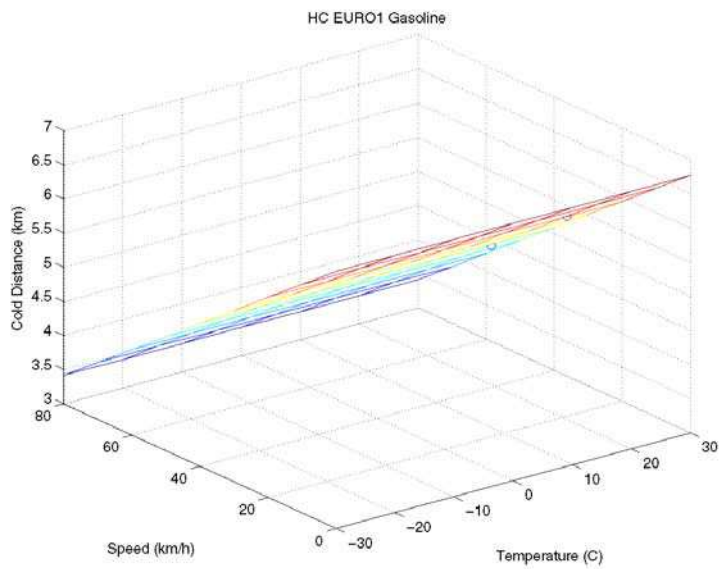
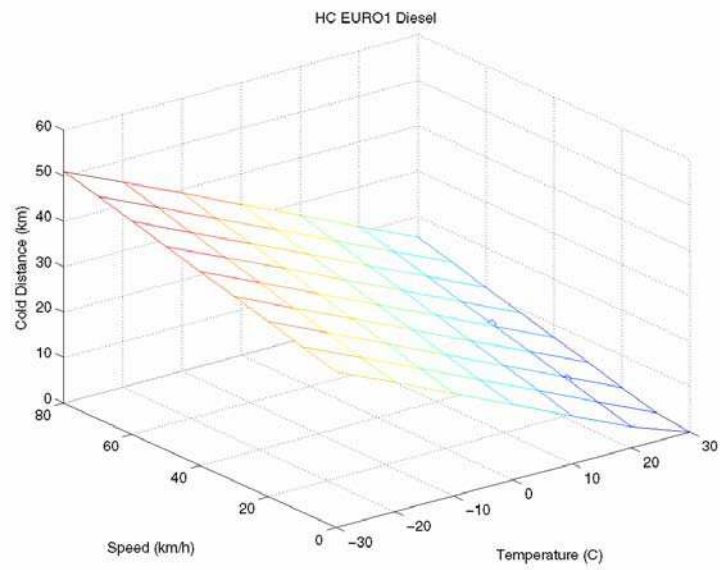


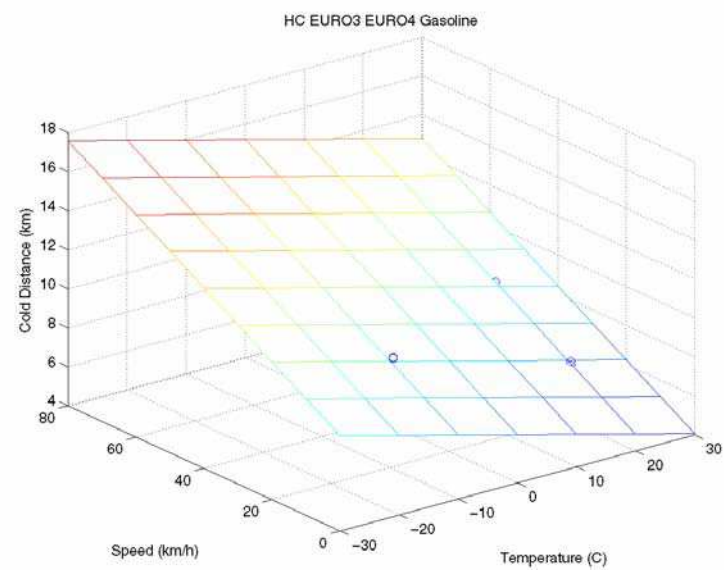
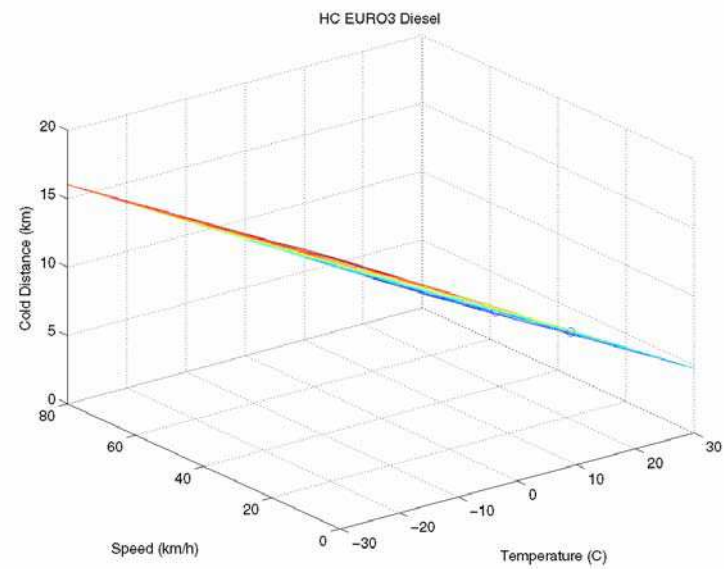
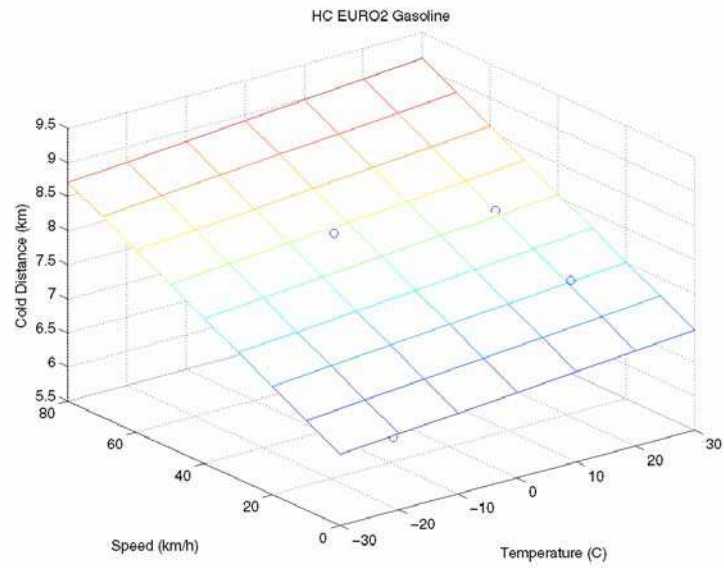




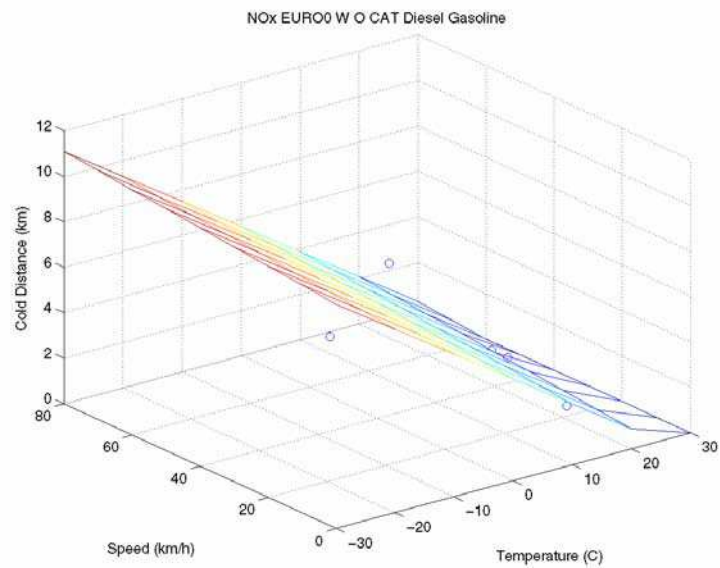
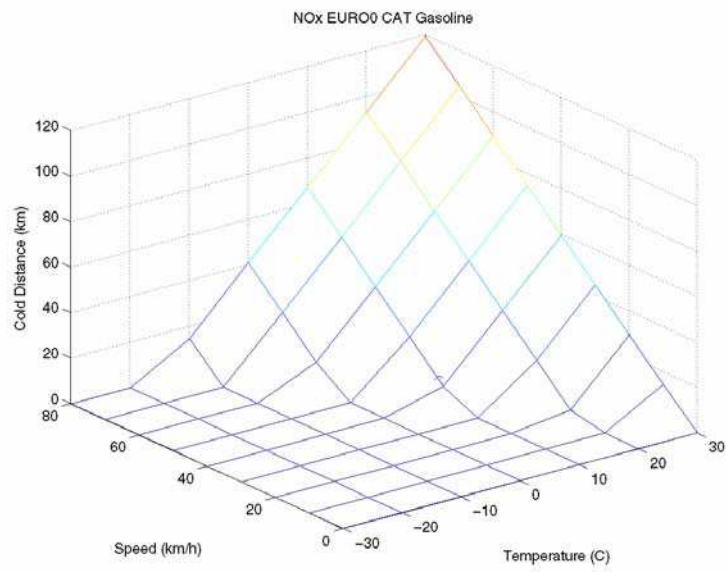
Annex 5.4: HC

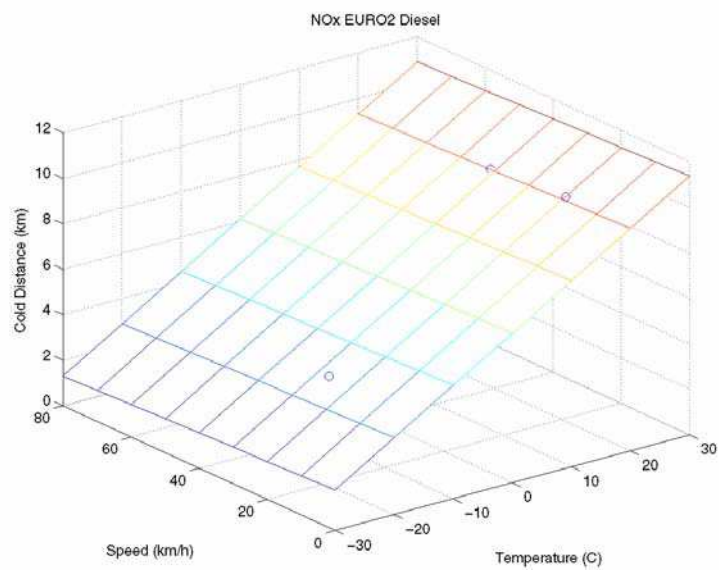
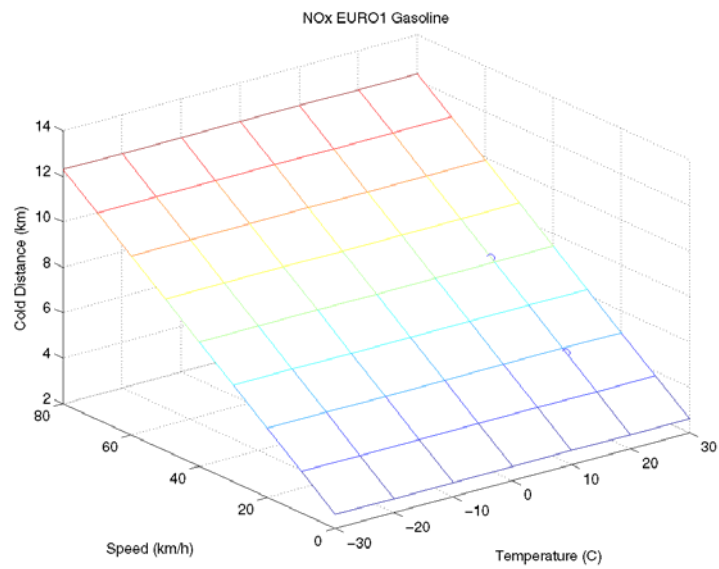
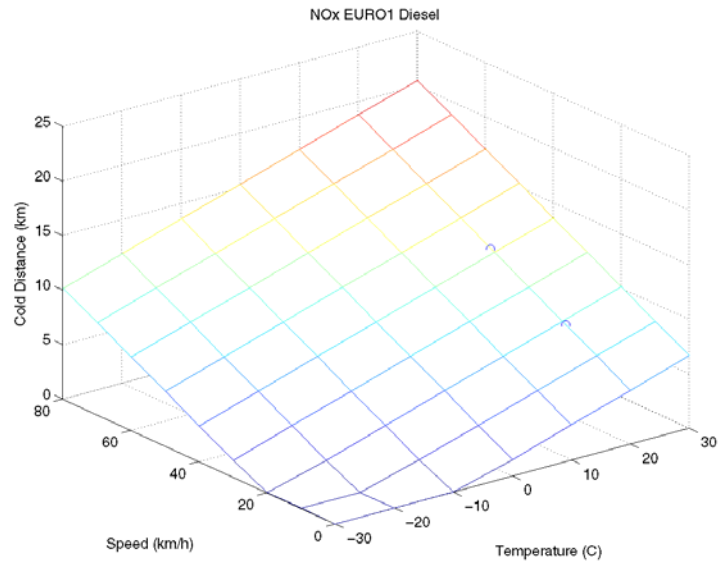


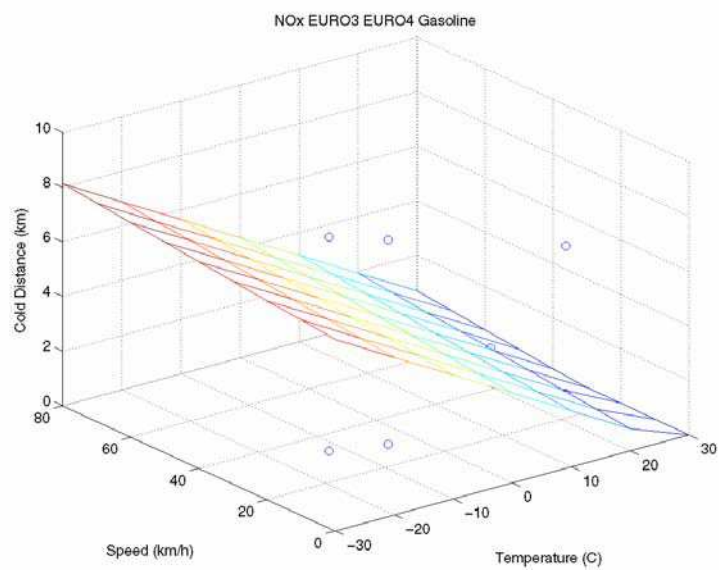
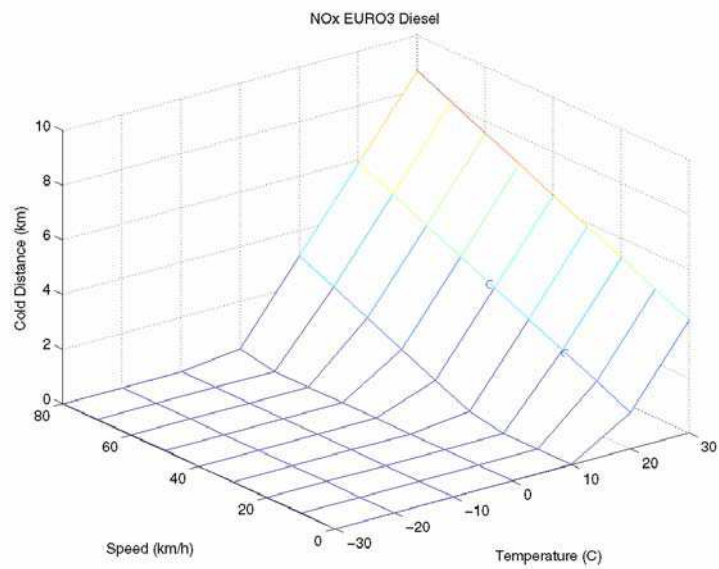
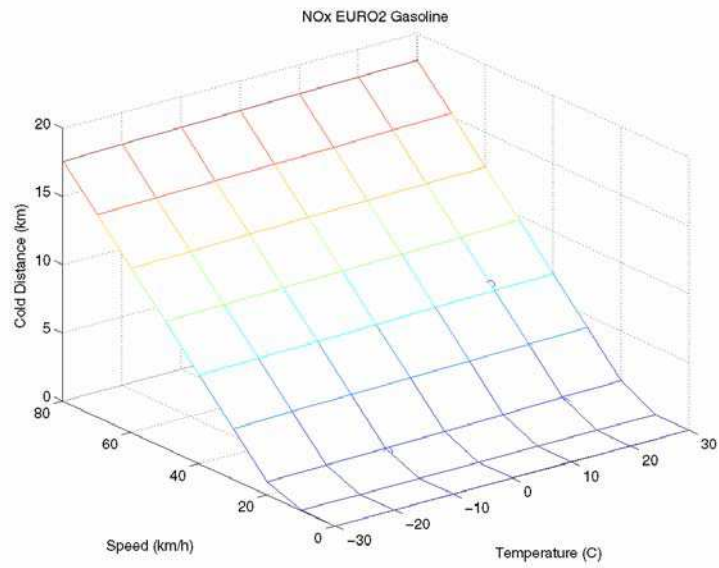




Annex 5.5: NOx





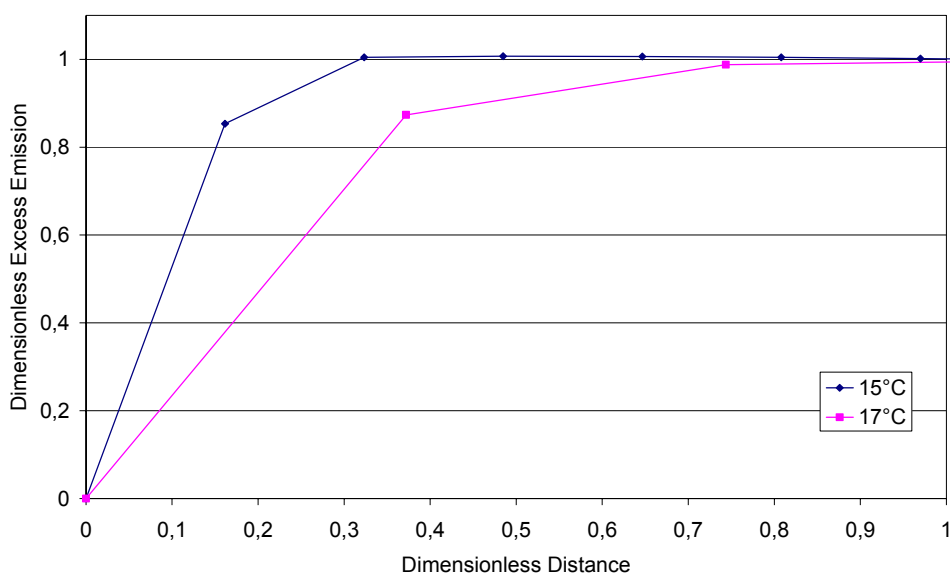


Annex 6: Dimensionless excess emission versus dimensionless distance

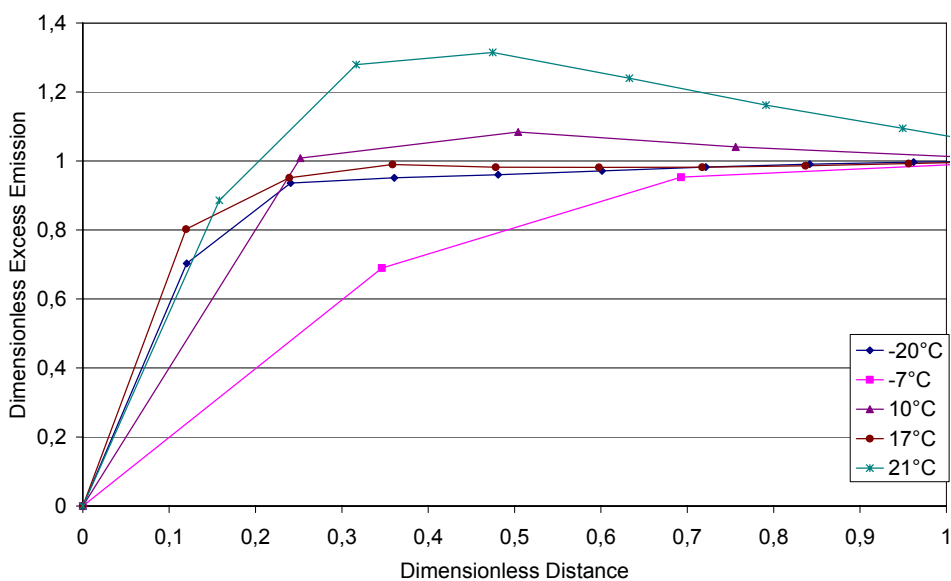
In the figures, one point is for a given dimensionless distance the dimensionless excess emission averaged over 2 cycle speeds (see section 1.1.).

Annex 6.1: CO

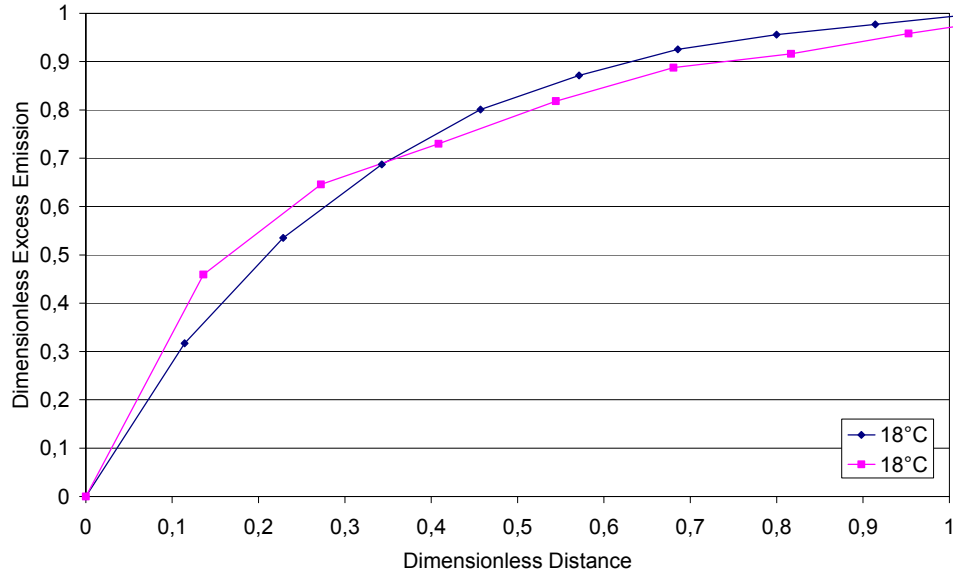
Euro 0 Cat.
Gasoline



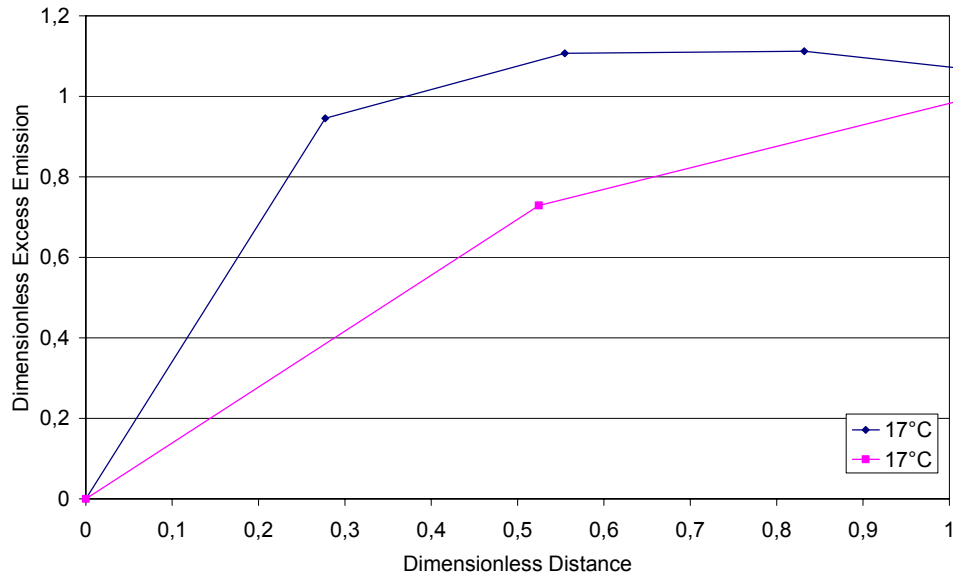
Euro 0 W/O
Cat. Gasoline
and diesel



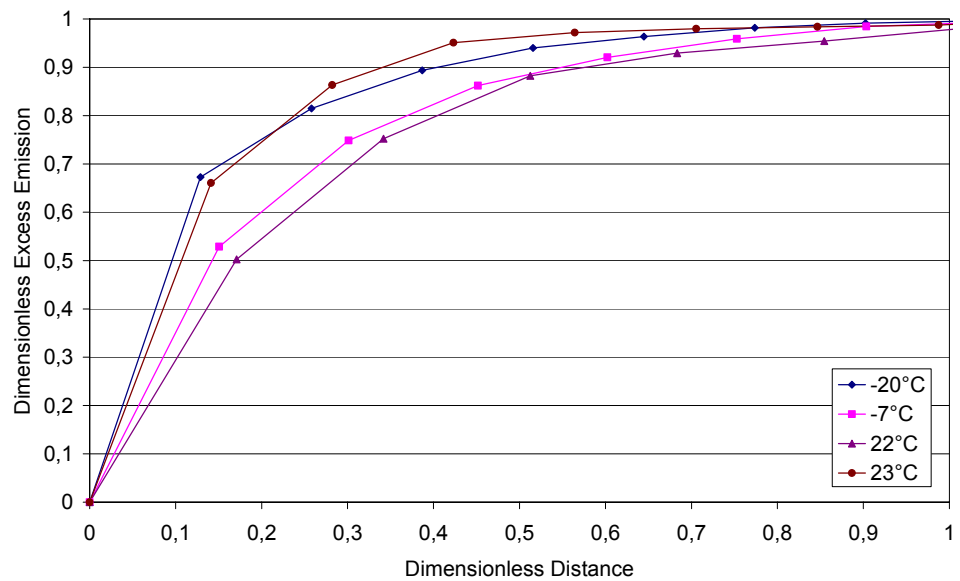
Euro 1 diesel



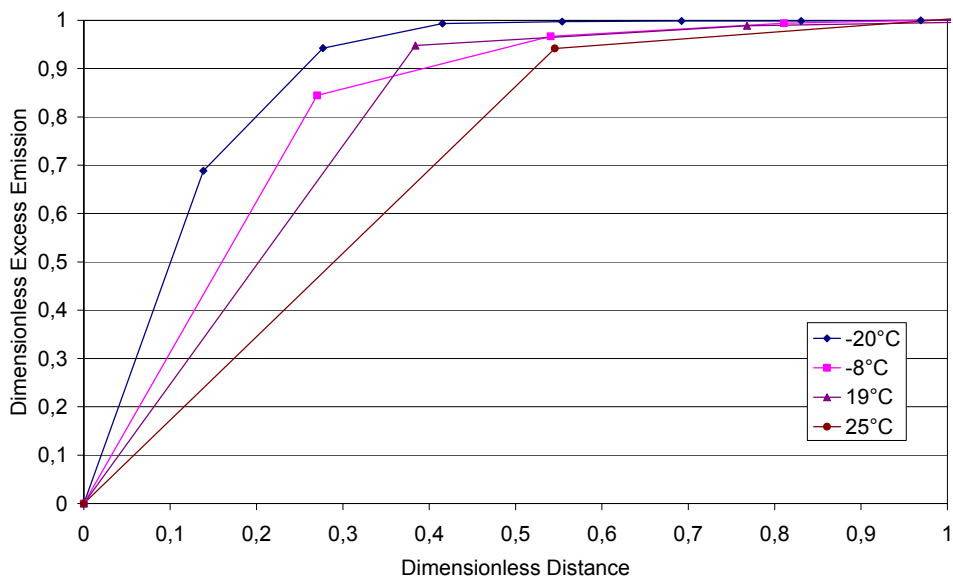
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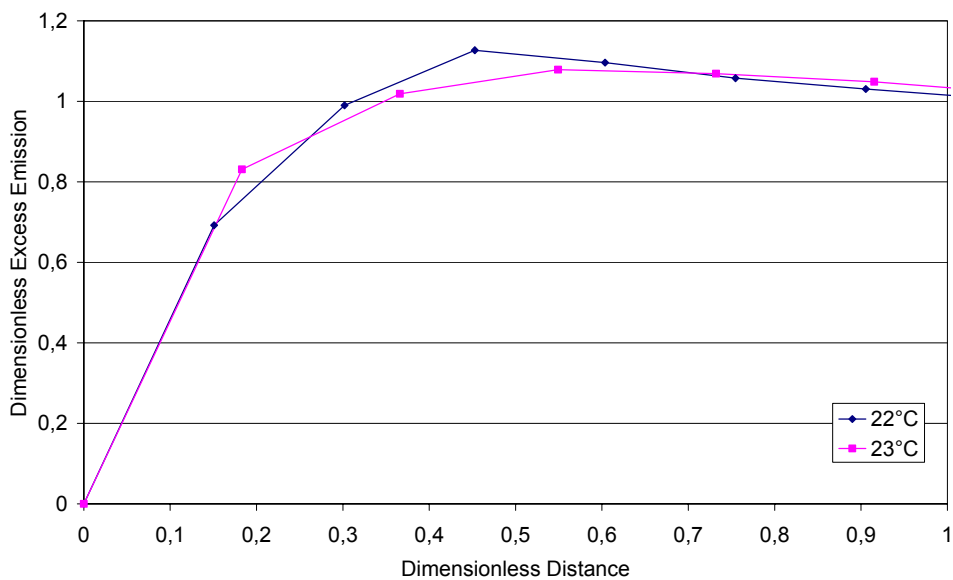
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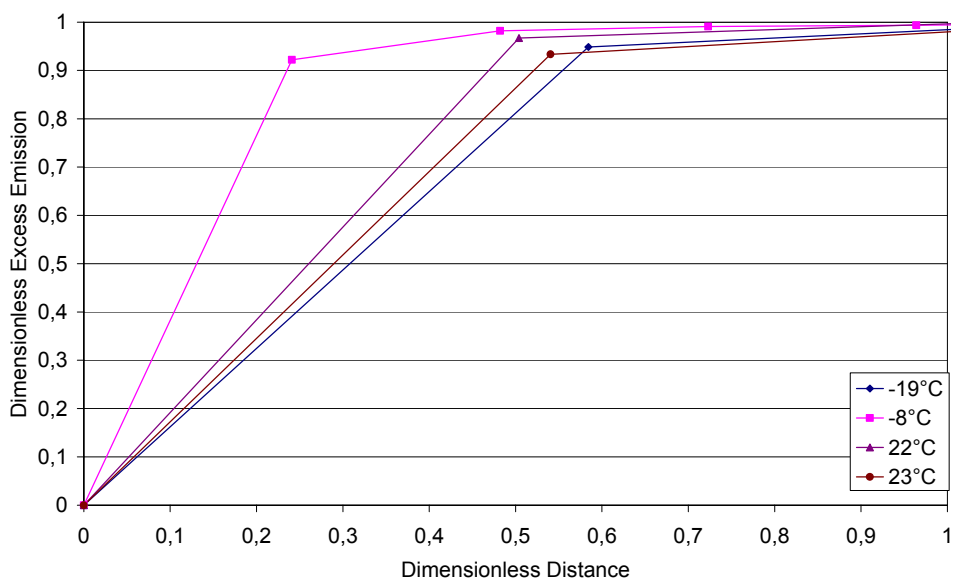
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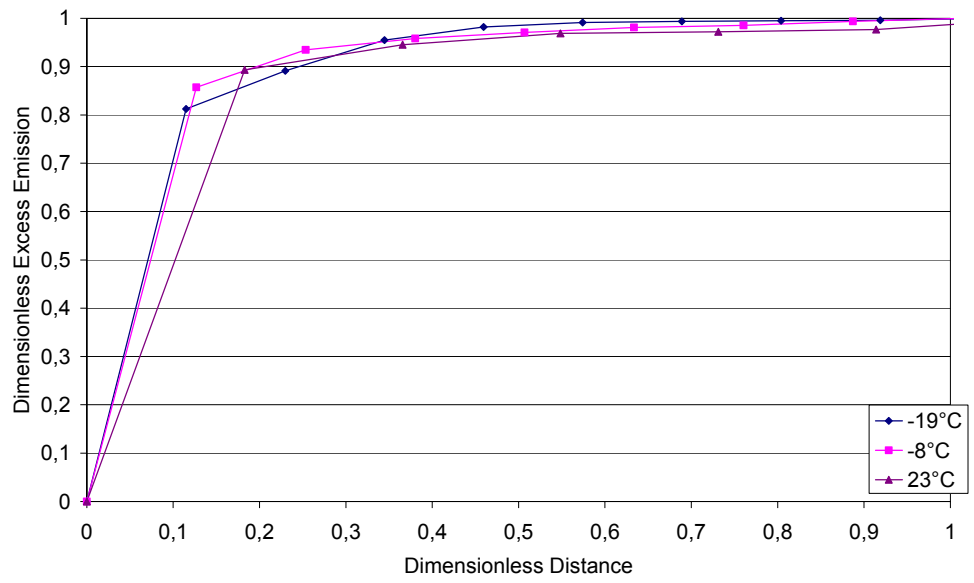
Euro 3 Diesel



Euro 3
Gasoline

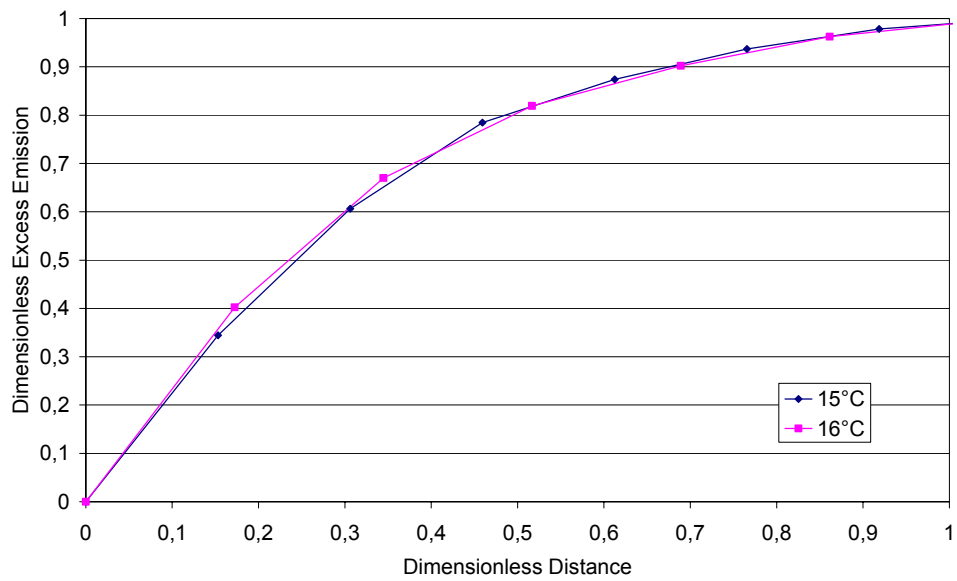


Euro 4
Gasoline

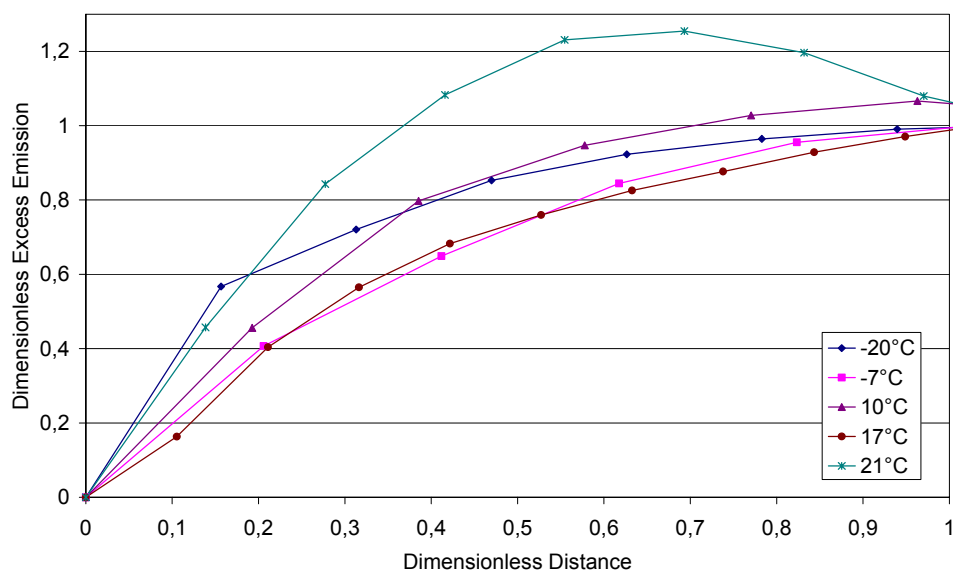


Annex 6.2: CO₂

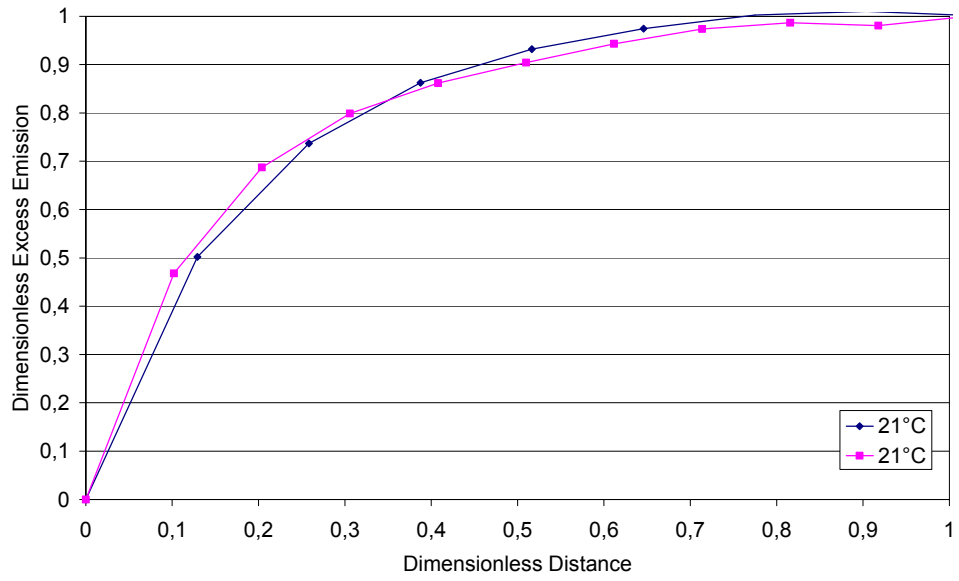
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Gasoline



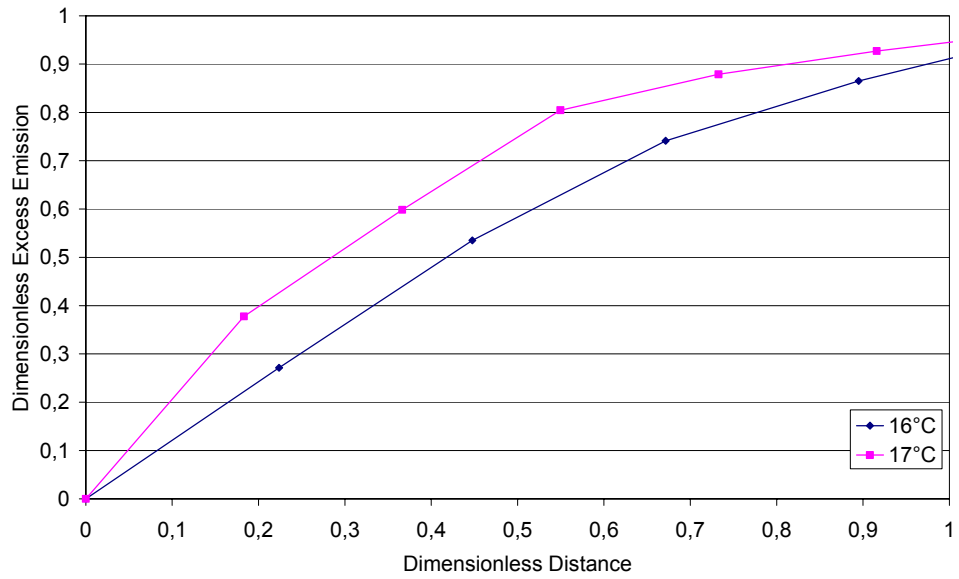
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Cat. Gasoline
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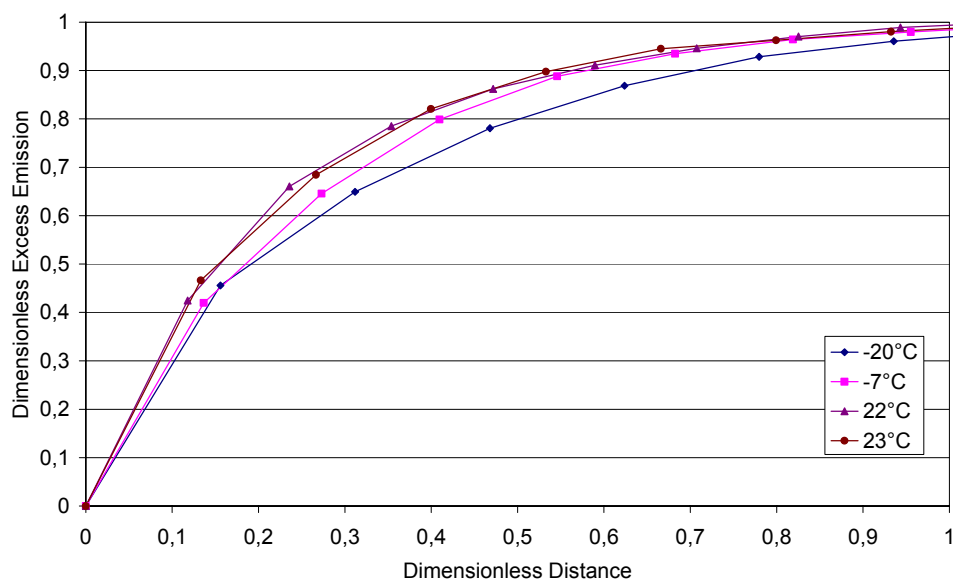
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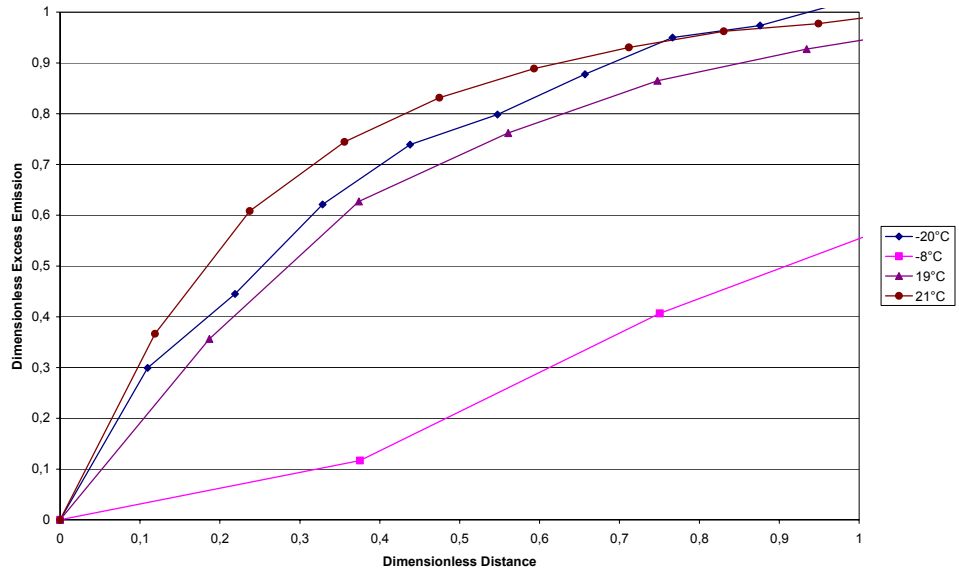
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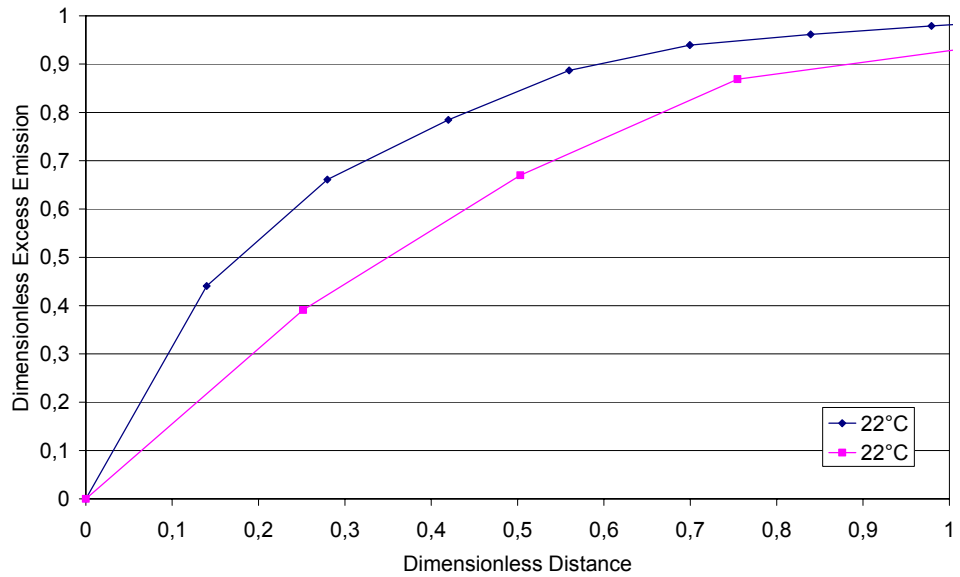
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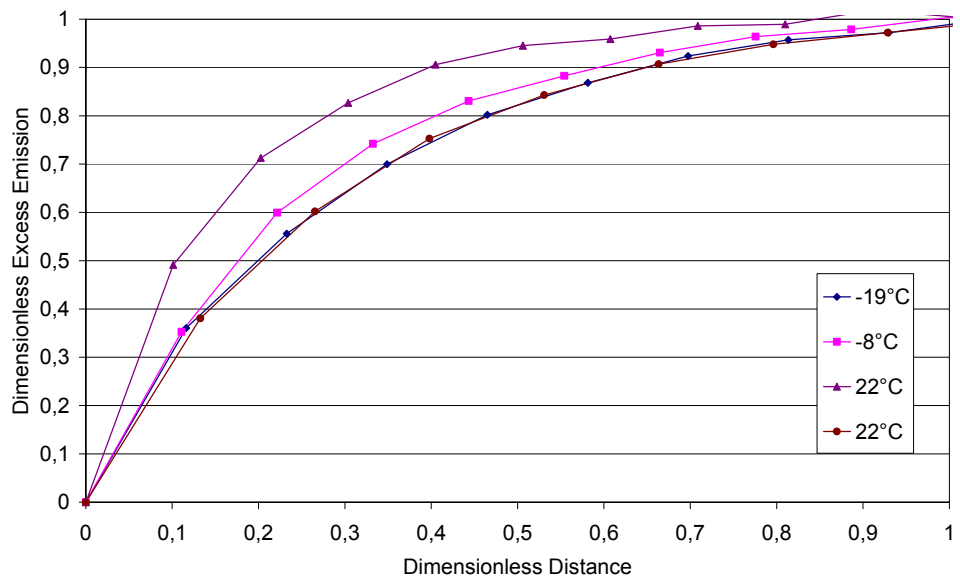
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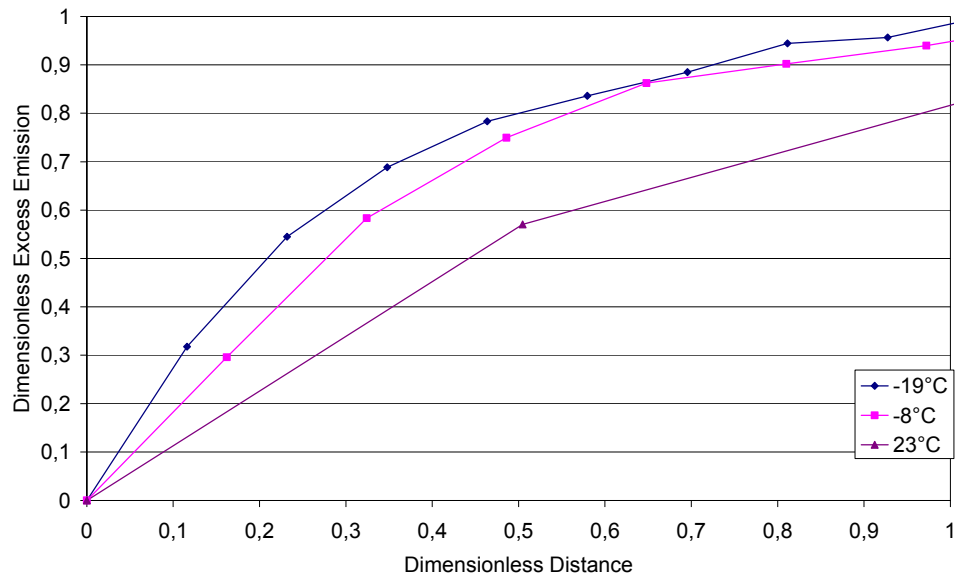
Euro 3 Diesel



Euro 3
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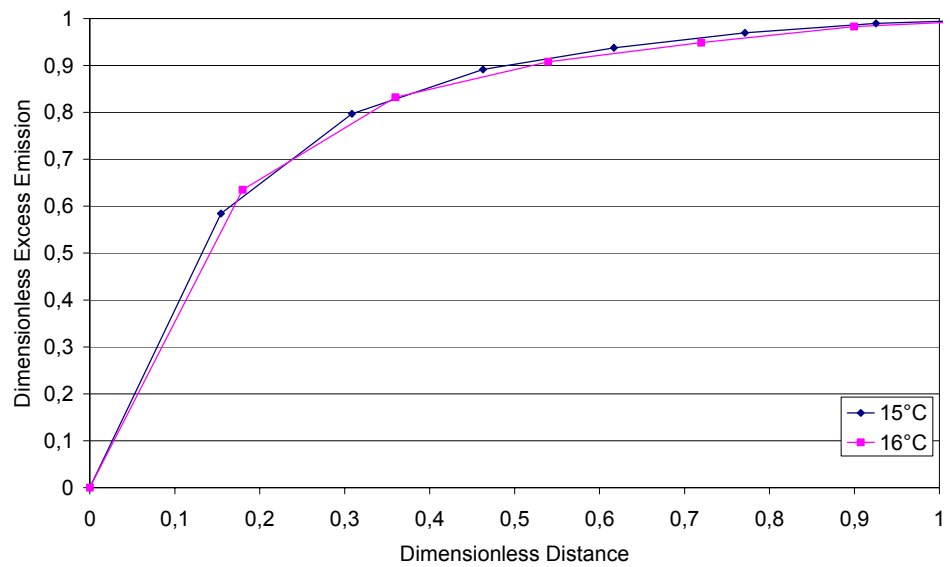


Euro 4
Gasoline

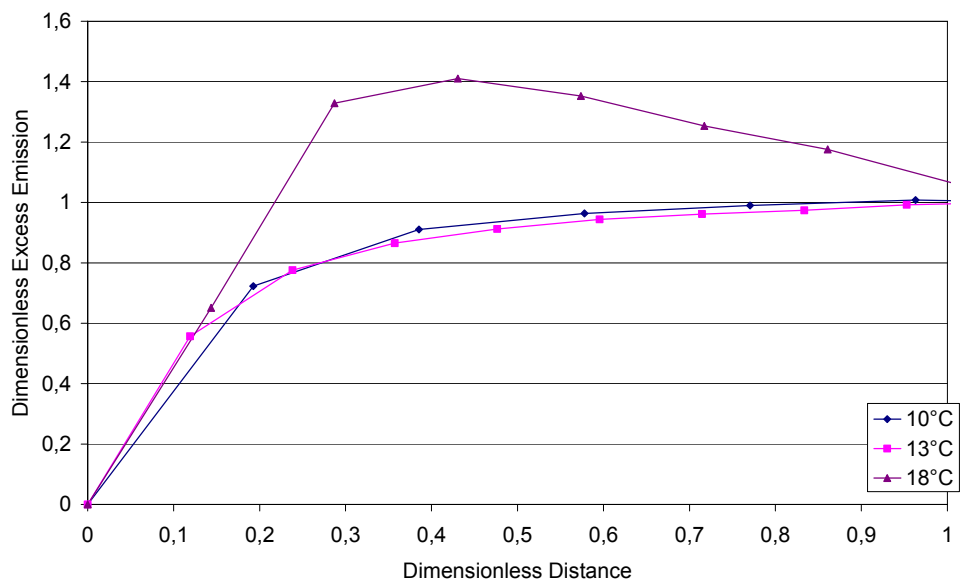


Annex 6.3: FC

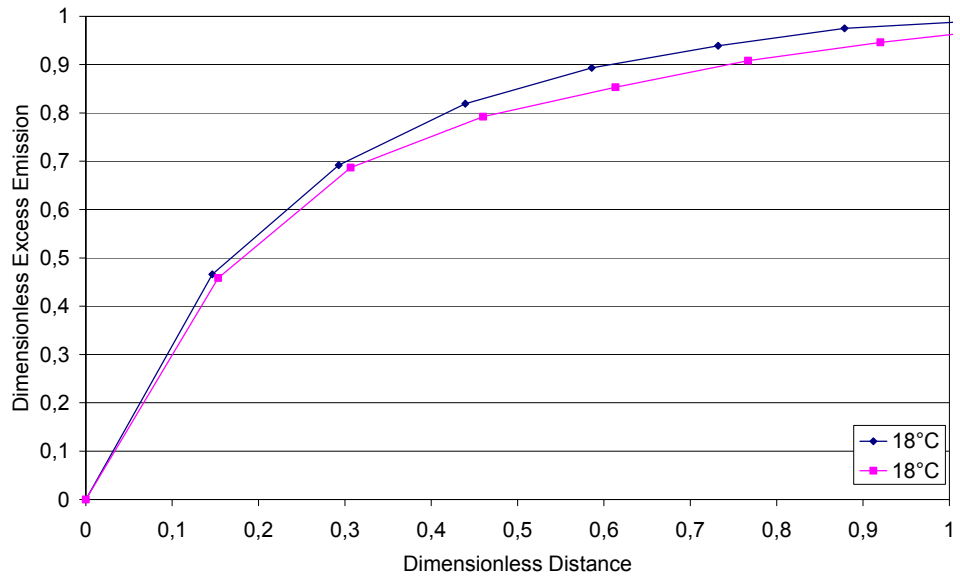
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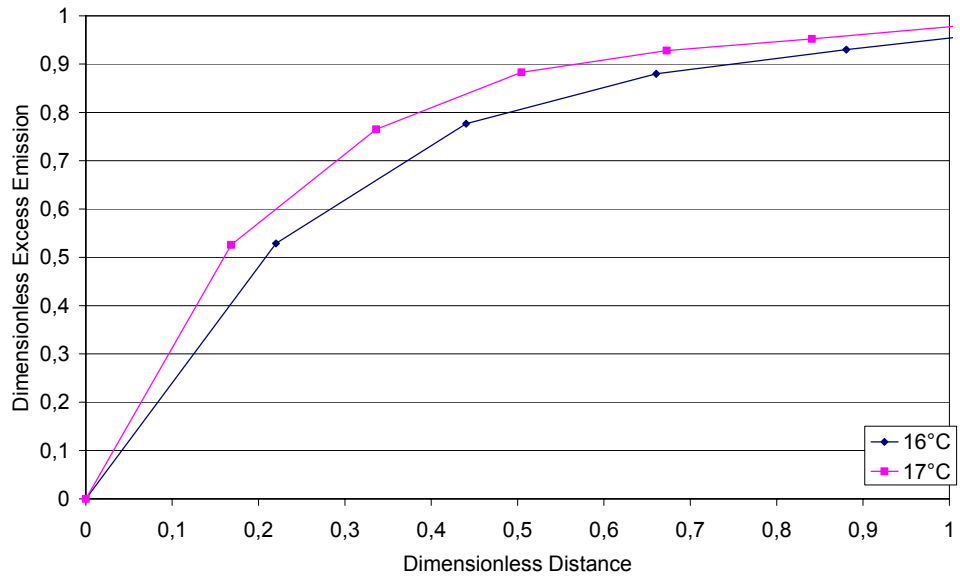
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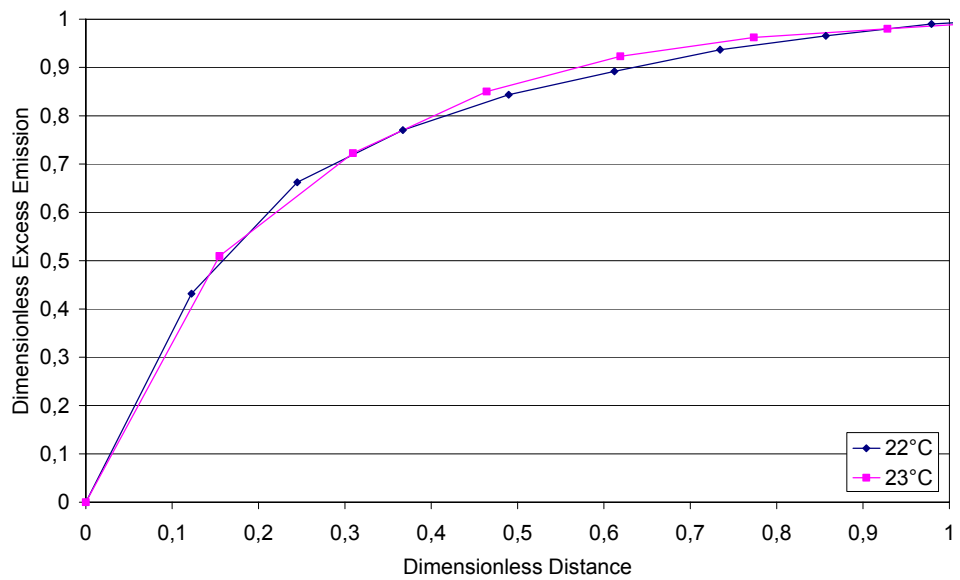
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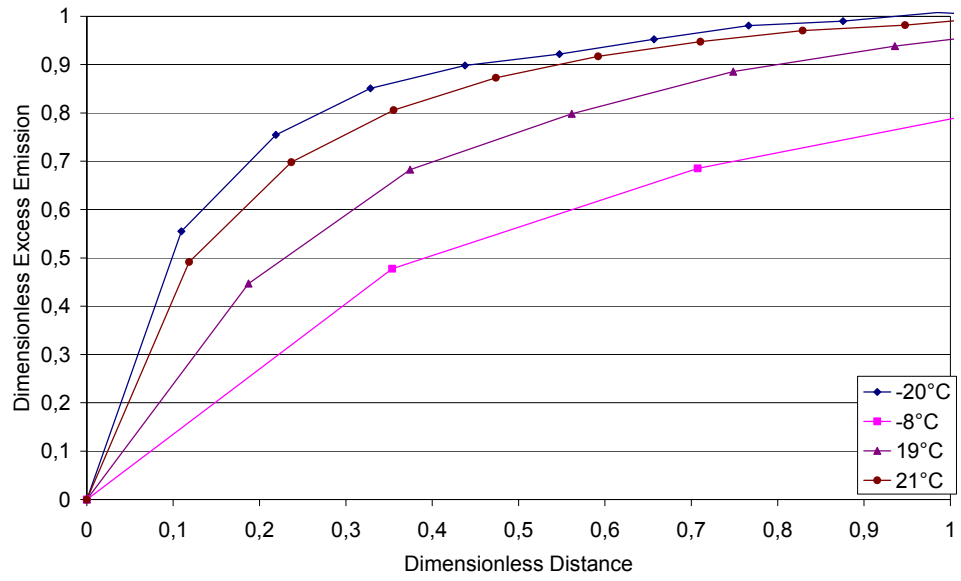
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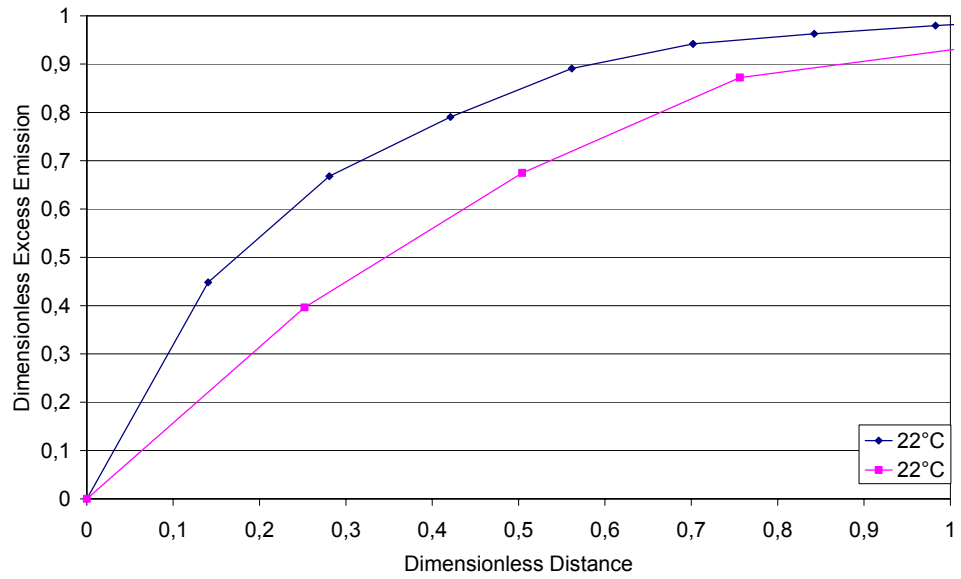
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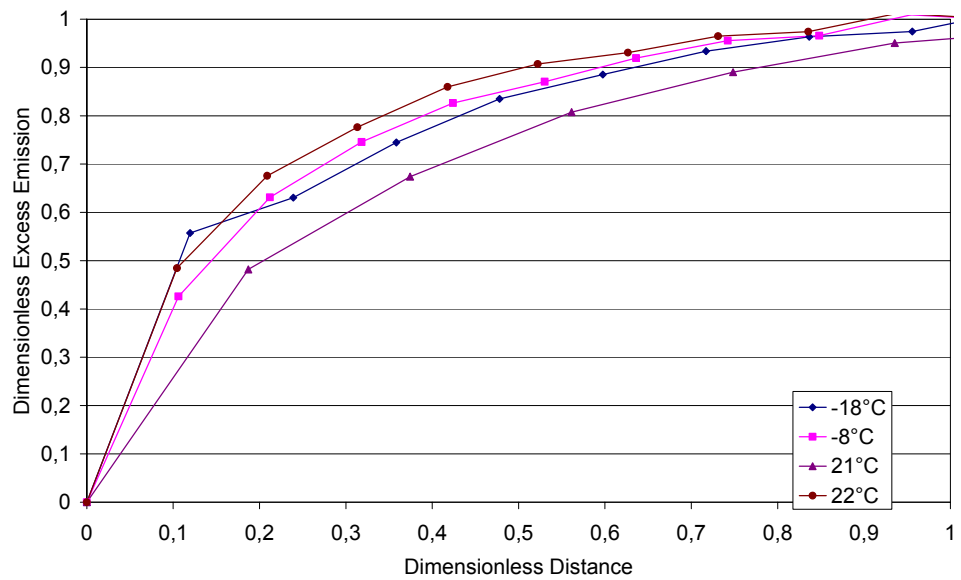
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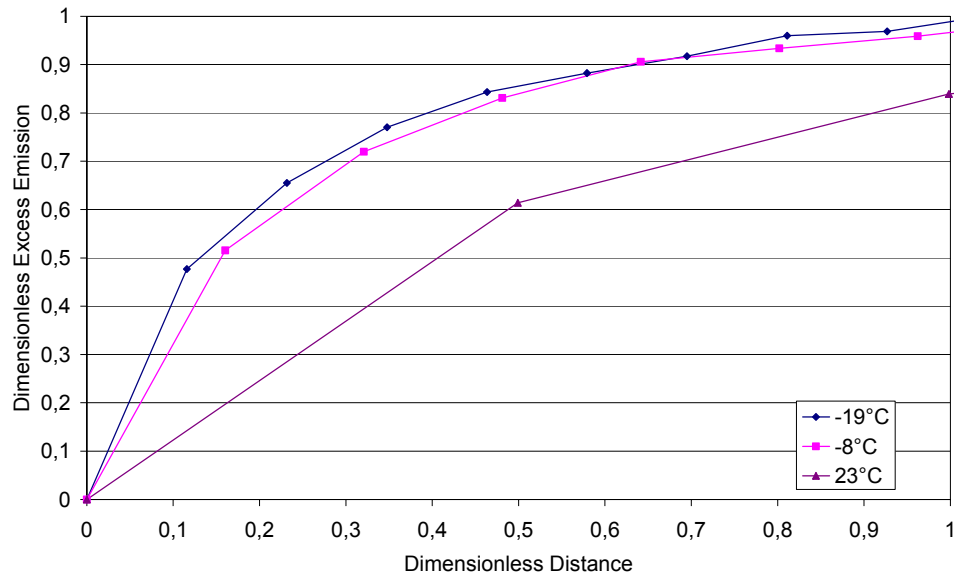
Euro 3 Diesel



Euro 3
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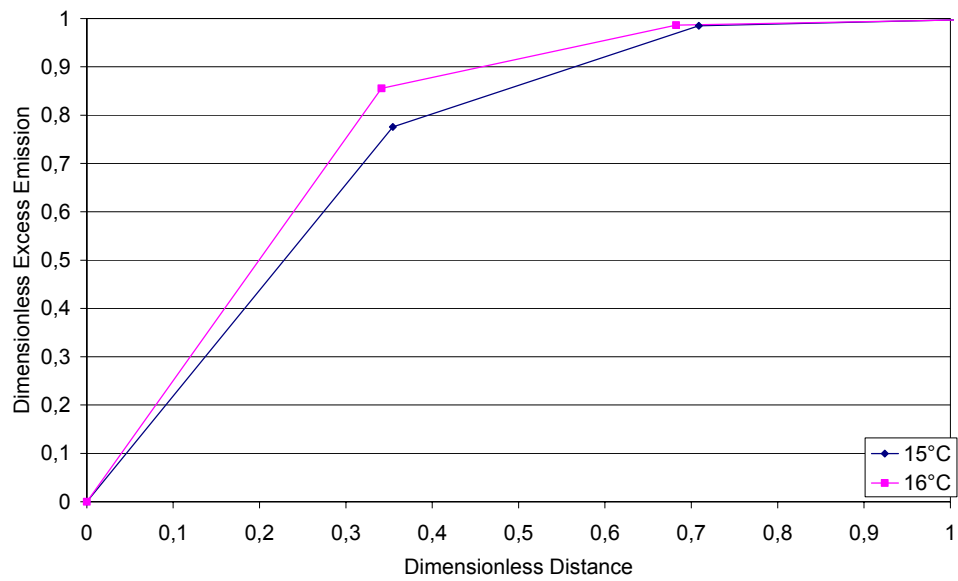


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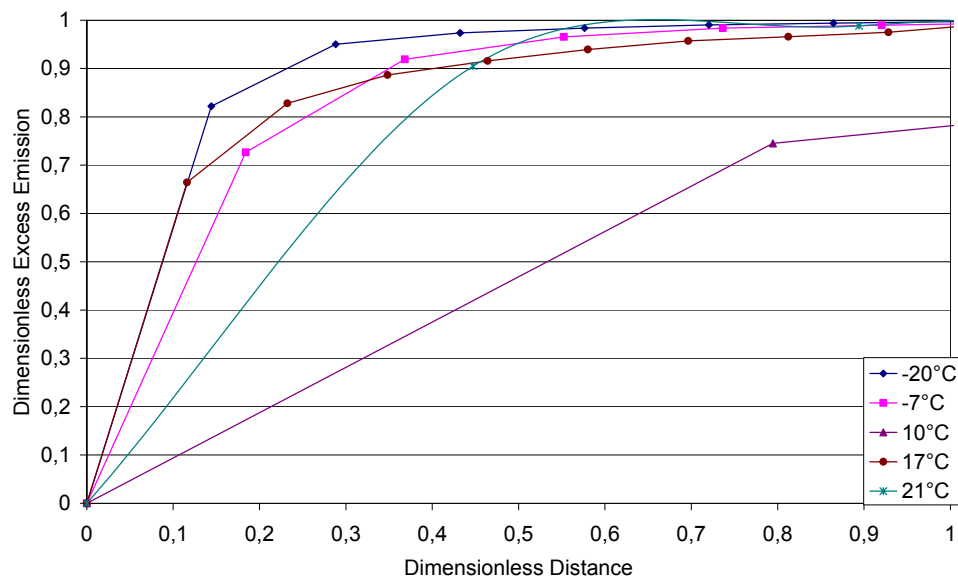


Annex 6.4: HC

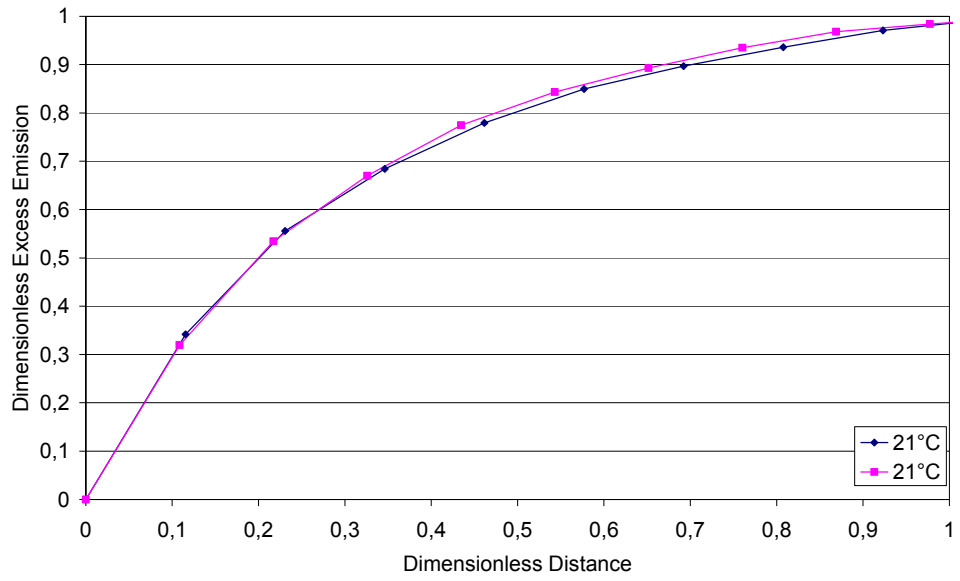
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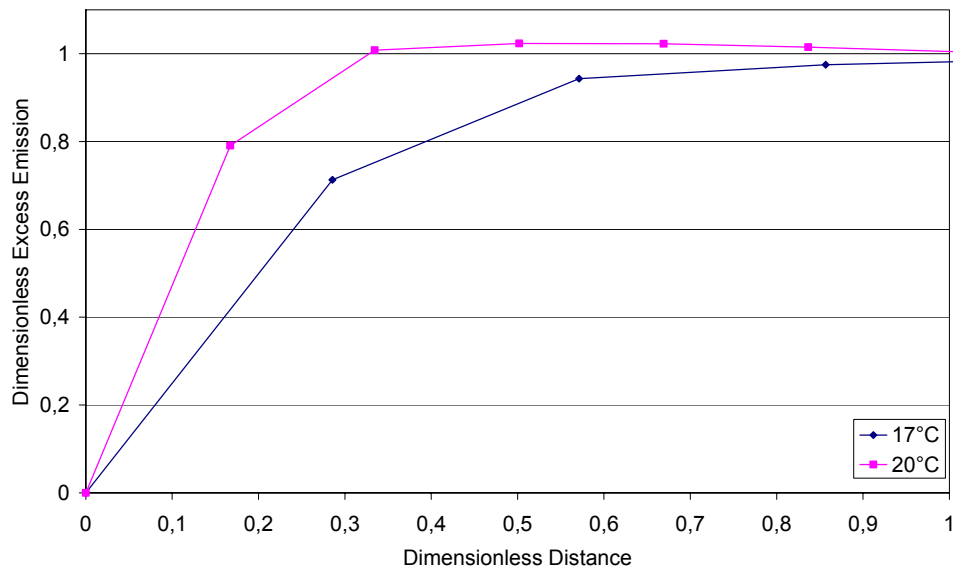
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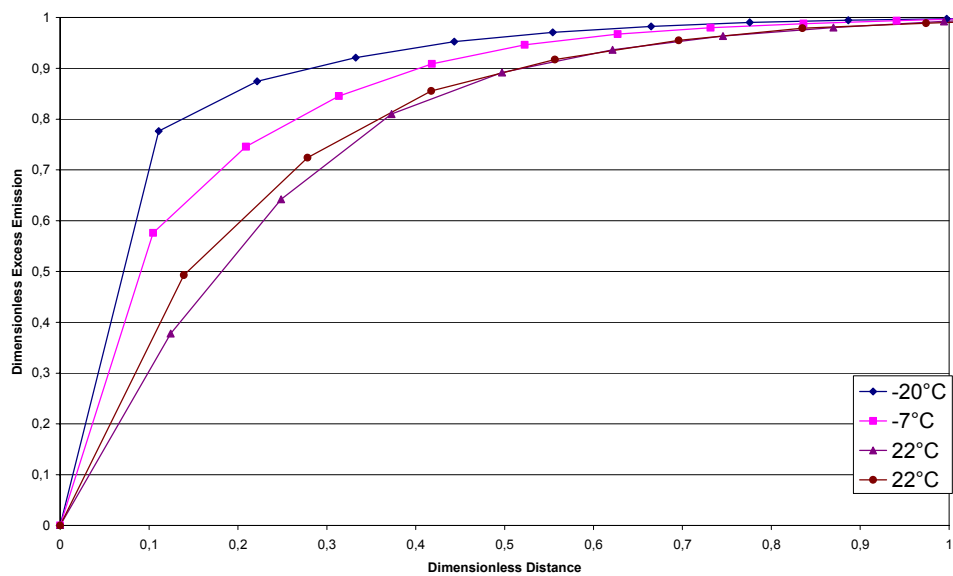
Euro 1 diesel



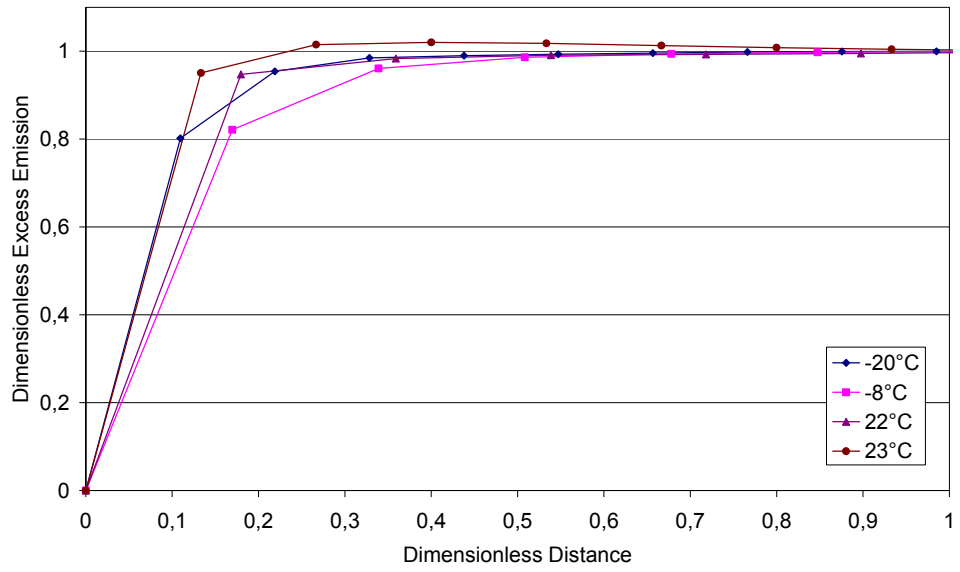
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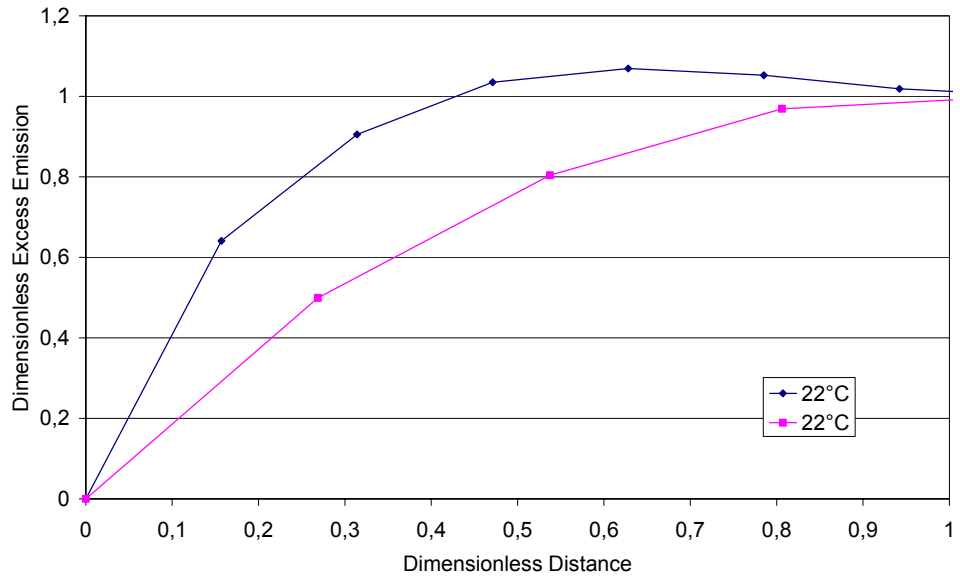
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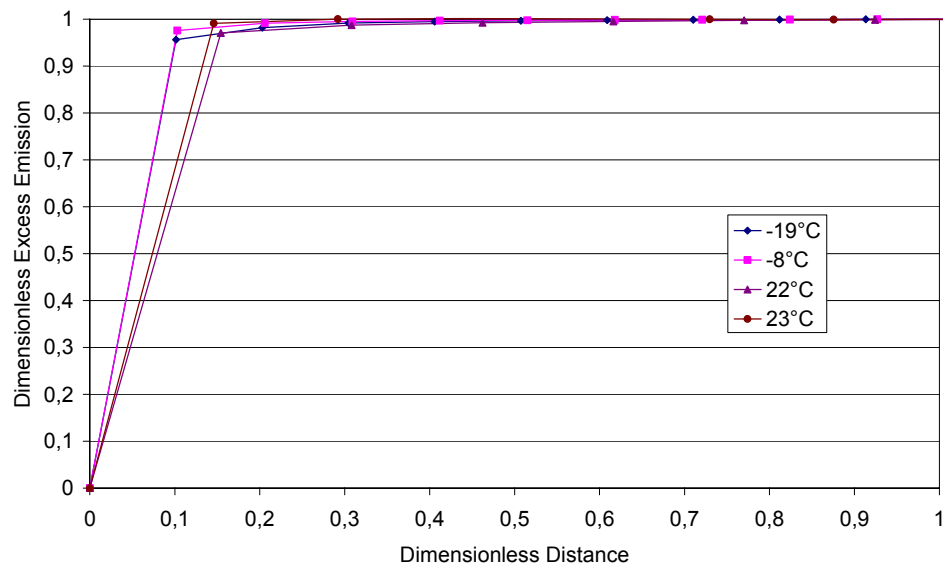
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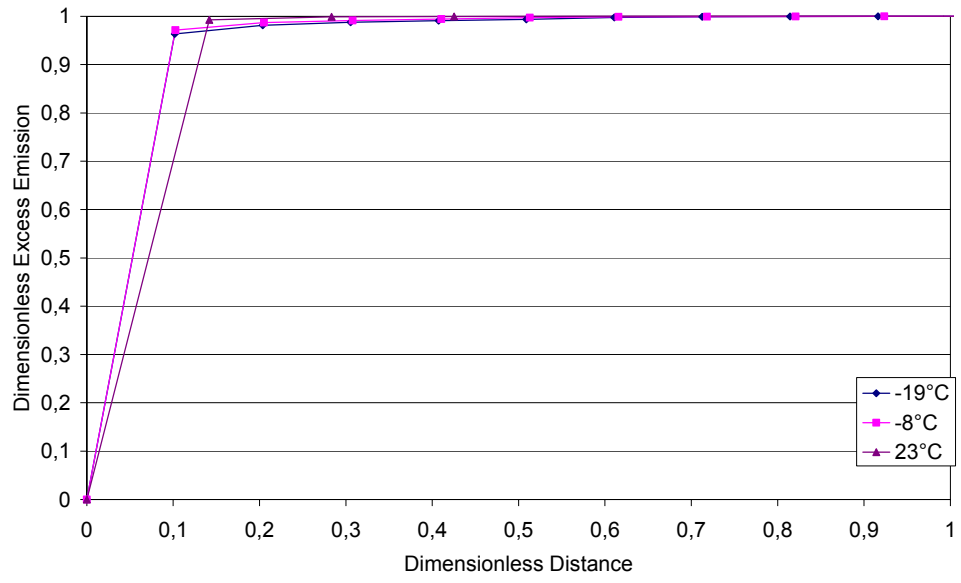
Euro 3 Diesel



Euro 3
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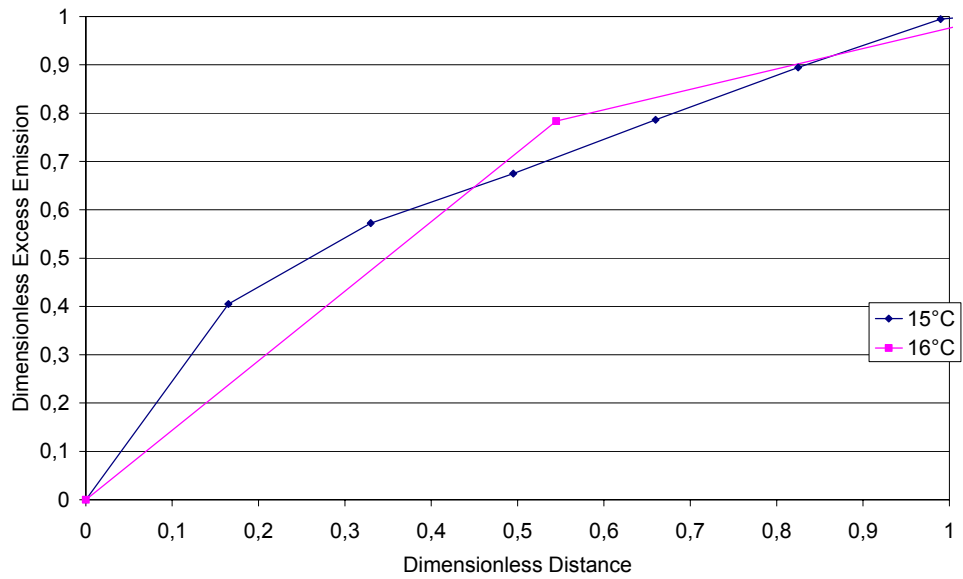


Euro 4
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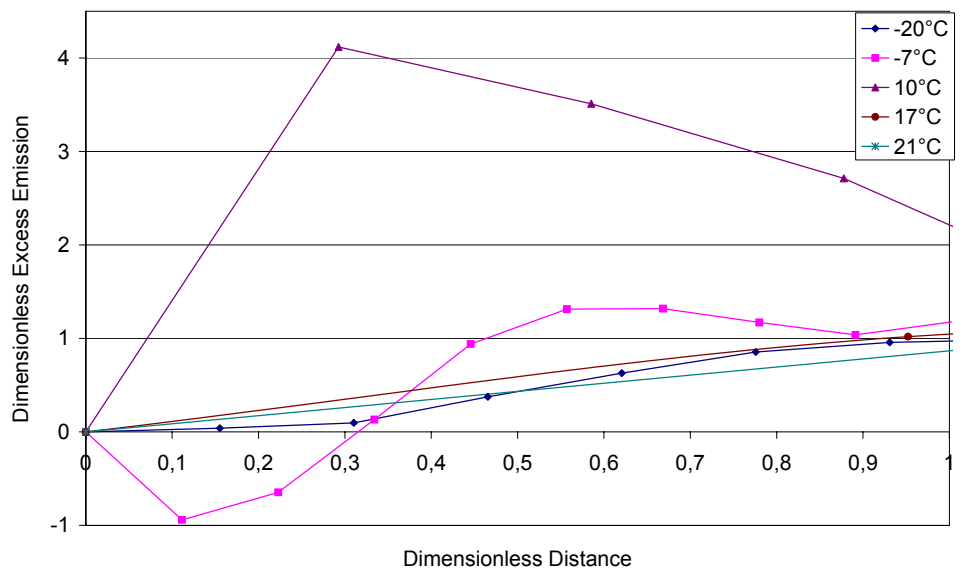


Annex 6.5: NO_x

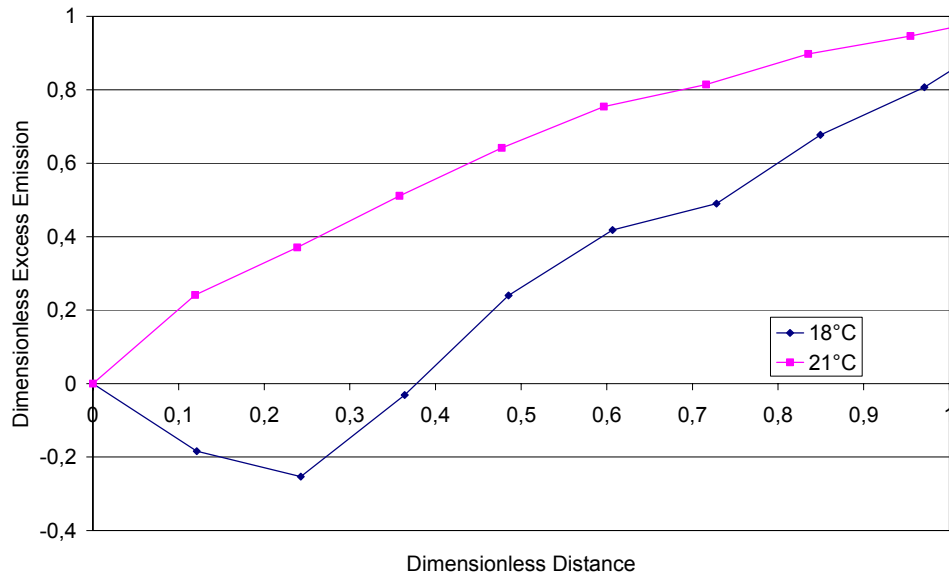
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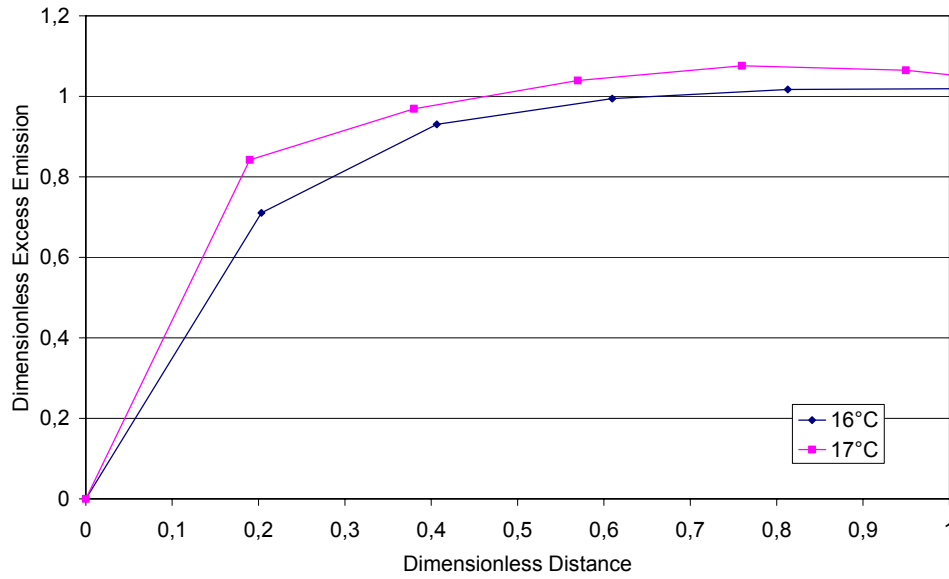
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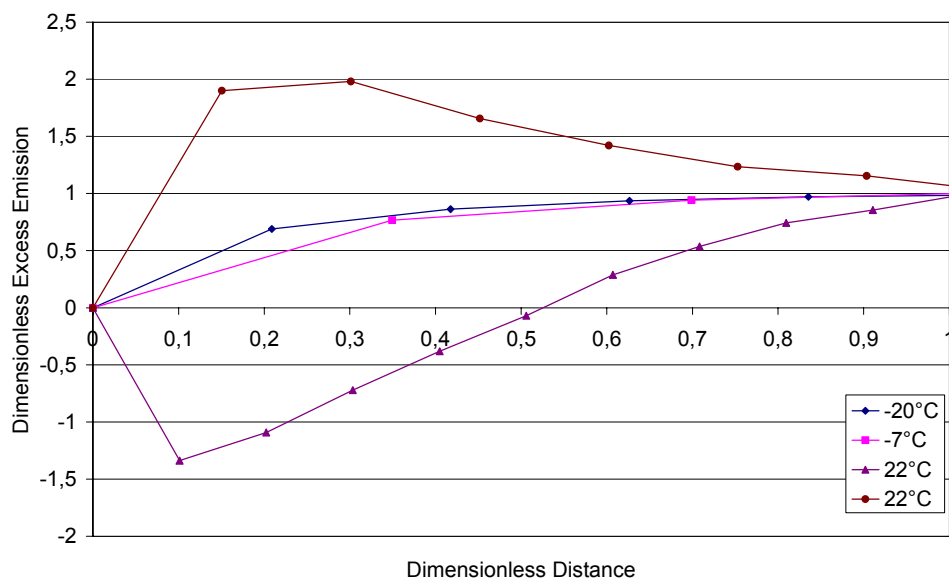
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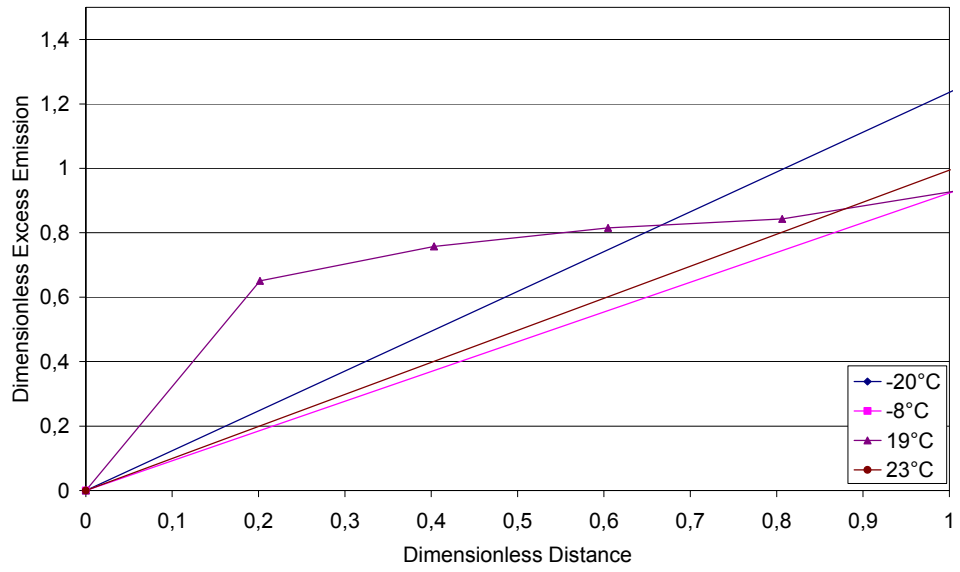
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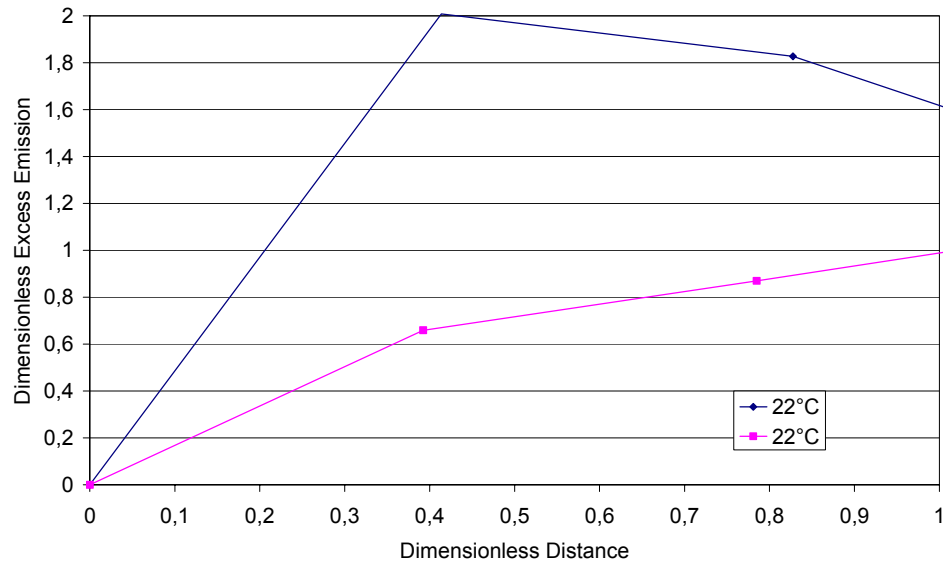
Euro 2 Diesel



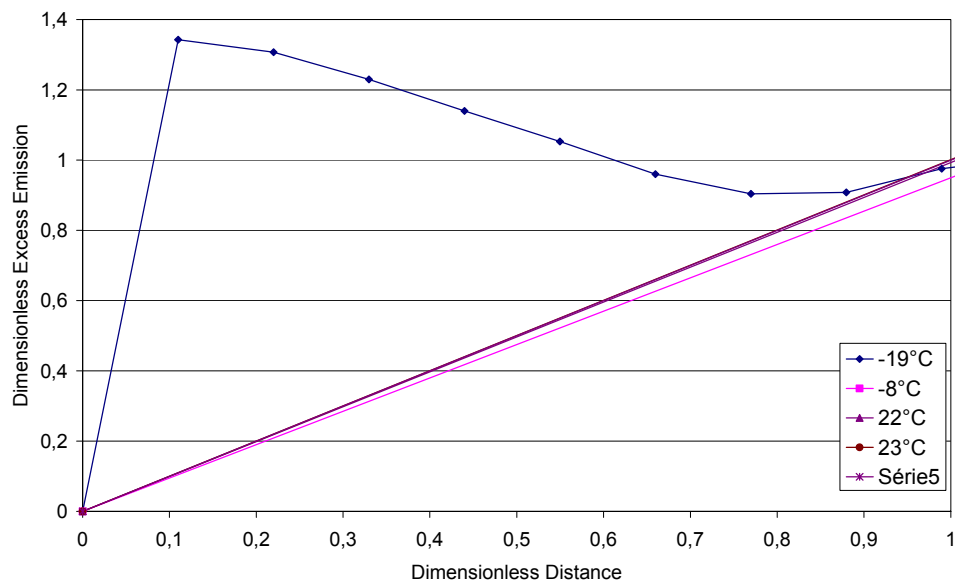
Euro 2 Gasoline



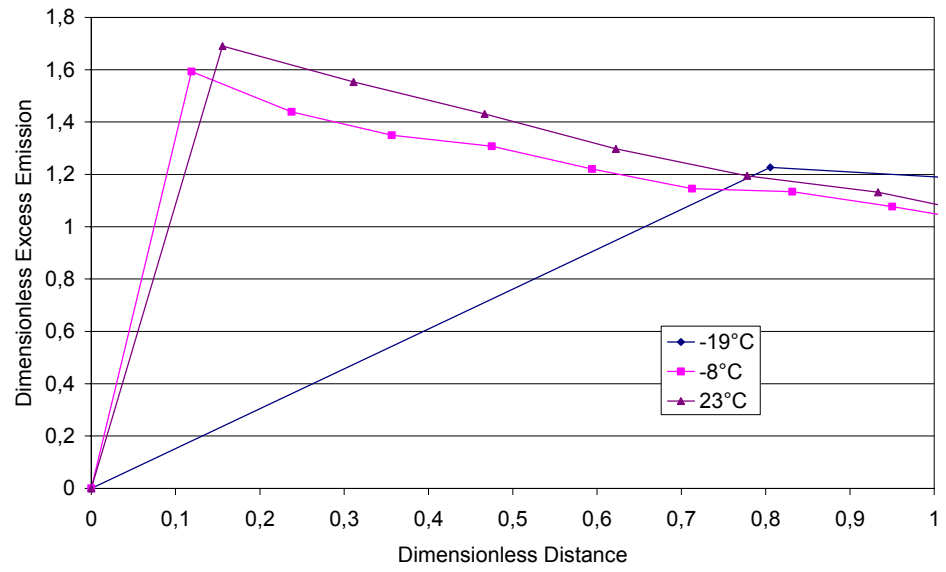
Euro 3 Diesel



Euro 3 Gasoline



Euro 4
Gasoline



Annex 7: Standard correction of NO_x emission according to humidity

According to E.P.A. (1976) and Lenner (1994), we present here the standard method to correct NO_x emission according to air humidity.

In order to define the hygrometric state of the atmosphere, the mixing ratio r can be used, expressed in grams of water vapour per kilogram of dry air. This ratio depends on the atmospheric humidity, the temperature and the total pressure:

$$r = 6.2198 \cdot \frac{U \cdot e'_w}{P - U \cdot e'_w \cdot 10^{-2}}$$

with

$$\left\{ \begin{array}{l} U : \text{relative humidity in \%} \\ P : \text{atmospheric pressure in kPa} \\ e'_w : \text{saturated vapour pressure in kPa ; } e'_w = 0.61121 \cdot \exp \left[\frac{\left(18.729 - \frac{T}{227.3} \right) \cdot T}{T + 257.87} \right] \\ T : \text{temperature in } ^\circ\text{C} \end{array} \right.$$

In order to compute the correction, multiply the emission by the factor K_H equal to:

$$K_H = \frac{1}{1 - 0.0266 \cdot (r - 10.71)} \text{ for FTP cycle}$$

$$K_H = \frac{1}{1 - 0.0329 \cdot (r - 10.71)} \text{ for ECE -15 cycle}$$

The first equation (FTP cycle) is valid for mixing ratio ranging between 2.86 g and 20.00 g of water vapour per kg of dry air, whereas, the second equation (ECE-15 cycle) is valid for ambient temperature between 20 °C and 30 °C and mixing ratio between 5.0 g and 12.2 g of water vapour per kg of dry air.

New correction factors are proposed within the Artemis project, different from the standard ones.

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