

# Emissions of Passenger Cars in Special Driving Situations

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## Abstract

Testing of real driving emissions (RDE), as an element of a type approval of passenger cars (since September 2017), offers the opportunity to collect the data about the emissions in special driving, or non-driving situations. These situations are: cold start, warm-up of the engine, stop & go and idling.

In the present work of the Laboratory for Exhaust Emissions Control (AFHB) of the Berne University of Applied Sciences (BFH), the definitions of the special driving situations were proposed and the emissions of 7 passenger cars (gasoline & Diesel) were extracted from the present RDE data.

Furthermore, some special driving situations, particularly the stop & go operation with varying share of idling were reproduced on chassis dynamometer.

As expected, the emissions of CO, NO<sub>x</sub> and PN are in the cold start and in the first part of the warm-up phase (c.a. 25s) considerably higher than in the rest of the investigated urban phase.

The singular emitting situations like “stop & go” or idling occur frequently in the warm-up phase, i.e. in the city operation when the engine and the exhaust system are still not warm enough.

The emissions in the investigated particular driving situations scatter considerably for the different vehicles due to varying efficiencies and warm-up of the exhaust aftertreatment systems.

## 1. Introduction

Emission factors and emission inventories are an important source of data for compiling and modelling the emissions of traffic in different situations. There is in EU a continuous work and development of emission data inventories, [1-5].

Since the introduction (in 2017) of the road-testing (RDE...real driving emissions) as an obligatory element of the legal testing procedures, the increased amount of RDE-data can be used for different objectives, such as: further development of emission inventories, compliance with “In-Service Conformity” (ISC, EU regulation 2018/1832) and market surveillance activities (EU regulation 2018/858). Extensive activities of testing RDE by means of PEMS (portable emissions measuring systems) have been performed in the last years, aiming not only the emissions but also the improvements of instrumentation, of testing procedures and of evaluation [4-12].

A well-known fact is that the emissions at cold start, during the warm-up and at the low speed phases of urban operation, both in the laboratory and on the road, tend to be higher for all pollutants, [9, 13-15]. This fact supports even the idea for future introduction of urban emission limits for the short trips, which are very frequent in Europe, [4].

In order to enable an automatic co-evaluation of emissions from the special (non)driving situations, the necessary definitions were proposed in the present work. With these definitions, the RDE data of 7 vehicles were processed and the emissions in special driving situations were obtained (part 1). Additionally, some special situations like cold start, warm-up and stop&go were reproduced on the chassis dynamometer with cars of different ages and different technology.

This paper gives some new insights in the topic of emissions from special driving situations.

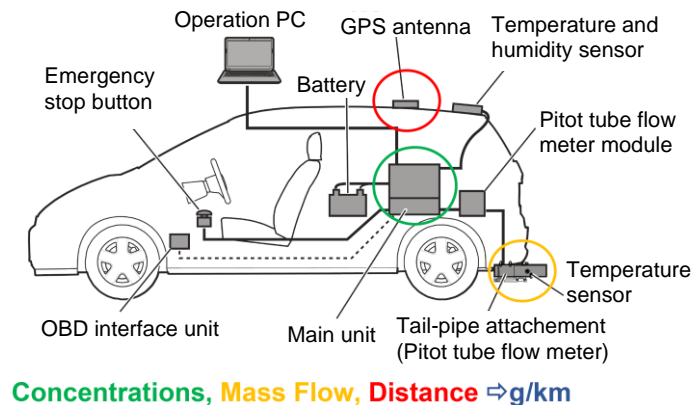
## 2. ANALYSIS OF PRESENT RDE DATA

### 2.1. Data origin & processing

The emissions data originate from testing of different vehicles with Horiba PEMS (Portable Emission Measuring Systems for gaseous emissions) and with PN-PEMS (for particle number PN) at AFHB.

The Horiba OBS-ONE-PN PEMS uses two-step dilution, a catalytic volatile particle remover (350°C) and an Isopropanol-based CPC as a main measuring unit.

Figure 1 represents the PEMS installation on a vehicle.



*Figure 1: Set-up of PEMS on a vehicle.*

The results of exhaust gas measuring devices are given as volume concentrations. Nevertheless, the legal limits are expressed in [g/km] for LDV, or in [g/kWh] for HDV. Therefore, it is necessary to install a flowmeter at the tailpipe of the vehicle and to estimate the instantaneous exhaust gas mass flow in the transient operation.

In the data processing, the vehicle positions and speeds are required. They are usually registered from the GPS (Global Positioning System), which is installed on the vehicle. If this signal is not available, e.g. in the tunnel, the speed can be obtained from the OBD-interface (on Board Diagnose) of the vehicle. Additionally, the parameters such as the engine coolant temperature and the engine speed are registered by the OBD.

The pollutant components measured by both PEMS (Gas & PN) are carbon dioxide CO<sub>2</sub>, carbon monoxide CO, nitric oxides NO<sub>x</sub> (consisting of NO and NO<sub>2</sub>) and particle number PN (considering the invisible nanoaerosol).

For the choice of data (vehicles previously measured in other projects) following criteria were taken into consideration:

- Version of the RDE route
- The same measuring system
- Engine cold start measured
- Engine start measured
- Emission components measured (CO<sub>2</sub>, CO, NO<sub>x</sub>, PN, HC)
- Start-stop-system (switched off).

Seven vehicles (three gasoline and four Diesel) could be chosen for the data evaluation. Table 1 summarizes the most important data of these vehicles.

Some criteria could not be completely fulfilled:

- Start-stop-system of LDV 07 was switched on
- PN was not measured for some vehicles
- HC was not measured for all vehicles

Table 1: List of vehicles chosen for the data evaluation (LDV ... light duty vehicle)

Nr.	Fuel	Displacement	Exhaust Aftertreatment System	Injection
LDV01	Gasoline	1.6	TWC	PFI
LDV02	Gasoline	4.0	TWC, GPF	DI
LDV03	Gasoline	6.2	TWC	PFI
LDV04	Diesel	2.0	DOC, DPF	DI
LDV05	Diesel	2.1	DOC, DPF, SCR	DI
LDV06	Diesel	3.0	DOC, DPF, SCR	DI
LDV07	Diesel	3.0	DOC, DPF, SCR	DI

## 2.2. Definitions of non-driving situations

### Distance driven and urban part

In the legal RDE-evaluation of LDV's the parts of driving, which were performed with the speed lower than 60 km/h, are considered as "urban", even if they were performed outside of the city. In opposition, the urban part in this work is defined as the first 13.7 km of the distance driven. This was decided after investigating the speeds, distances and emission traces of the chosen vehicles. 13.7 km is the shortest distance before one of the vehicles reached the speed of 60 km/h. With this definition of urban part, it is fixed that all investigated vehicles were driven below this speed limit value (60 km/h). Furthermore, it was observed that during this 13.7 km, there were the specific driving-and emissions-situations, which are the subject of this research: cold start, warm-up, stop&go, idling.

The investigation of the high-speed driving parts – rural and highway – showed no noticeable emission events.

### Cold start

The cold start is defined with the engine coolant temperature (ECT) as:  $(ECT + 2^{\circ}C) < t_{amb}$ , or  $ECT < 30^{\circ}C$ . This means that ECT can be up to  $2^{\circ}C$  higher than the ambient temperature or it must be lower than  $30^{\circ}C$ . This definition originating from the HDV-legislation is applied in this work because it is stricter than the definition from the LDV-legislation ( $+7^{\circ}C$ ,  $35^{\circ}C$ ).

### Engine warm-up

The warm-up time is defined in two ways:

- from the engine start ( $n > 500$  rpm) to the instant of  $ECT = 70^{\circ}C$  – this is named: "ECT 70" and
- from the engine start ( $n > 500$  rpm) to the duration of 5 minutes – this is named: "5 minutes".

These definitions and examples of the warm-up for two vehicles (gasoline & Diesel) are represented in [Figure 2](#). It can be clearly remarked that the Diesel vehicle needs a longer time to attain the ECT 70.

[Figure 5](#) summarizes the time-traces of ECT for all investigated vehicles. For LDV1 and LDV5, there are some irregular increases of ECT. ECT of LDV1 reaches  $70^{\circ}C$  in approximately 4 minutes after start. However, it falls again below  $70^{\circ}C$  for approximately 1 minute. This 1 minute is accounted to the warm-up according to the definition.

For more detailed analyses it is useful to consider both warm-up definitions and the time-courses of the increasing ECT.

### Stop&go

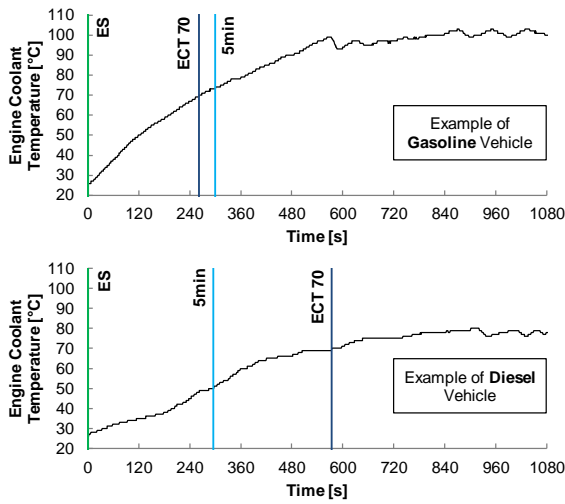
According to ASTRA, the definitions of traffic congestion which are used for the public traffic information are:

- the traffic jam on the extra-urban route is given when the speed is below 10 km/h during at least 1 minute and frequent standstill occurs,
- in the city circulation, the traffic jam is considered when the loss of summary time is over 5 minutes.

These definitions are close to the stop&go operation and they gave the basis for the definition which is easy to understand and which depicts well this driving situation.

The operation of the vehicle with the driving speeds between 1km/h and 10 km/h is considered as a "stop&go" phase. In this way, the vehicle standstill (stop) and the short acceleration by moving (go) are included in this operation mode.

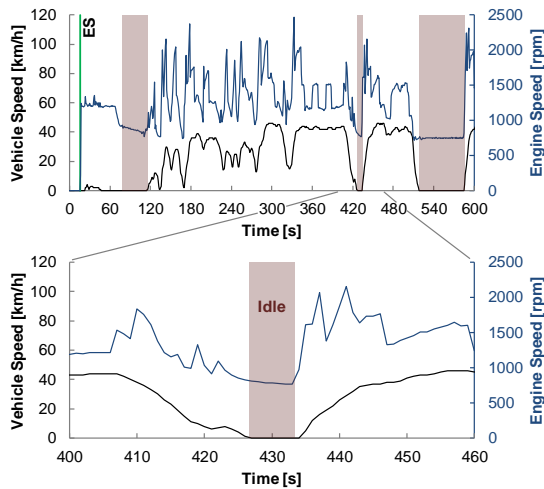
[Figure 3](#) shows the definition and example of stop&go in the urban part (13.7 km). [Figure 5](#) summarizes the shares of stop&go in the urban part for all investigated vehicles. These shares are in the range of 13% to 19%.



ES: Engine Start (Start of "Engine In Operation")  
 ECT 70: Engine Coolant Temperature (ECT) reaches 70°C  
 5min: 5min after Engine Cold Start

Definitions	start	end
Cold Start	state ECT < T <sub>ambient</sub> +2°C OR ECT < 30°C	-
Engine in Operation	state Engine Speed > 500 rpm	-
Warm-Up ECT 70	phase Cold Start AND Engine in Operation	ECT > 70°C
Warm-Up 5min	phase Cold Start AND Engine in Operation	Phase Time > 5min

Figure 2: Definition of warm-up in RDE-test



ES: Engine Start (Start of "Engine In Operation")

Definition	start	end
Idling	state 500 rpm < Engine Speed < 900 rpm	-
Idle	phase Vehicle Speed < 1 km/h AND Idling	Idle Start Cond. False

Figure 4: Definition of idling in RDE-test

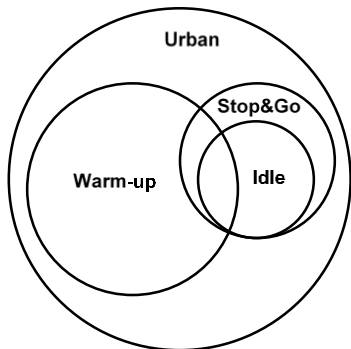
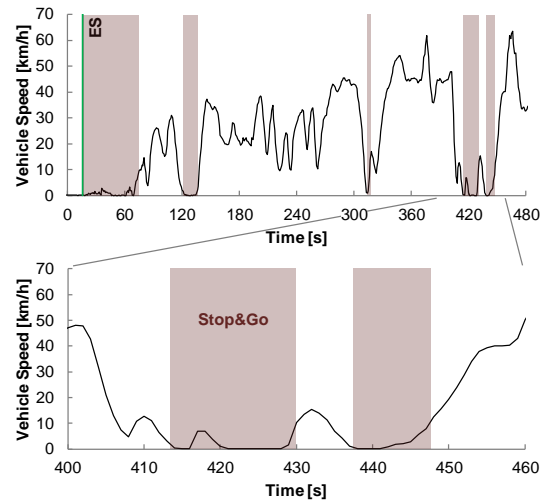


Figure 6: Qualitative overlapping of the analyzed data



ES: Engine Start (Start of "Engine In Operation")

Definition	start	end
Stop&Go	phase Vehicle Speed < 1 km/h	Vehicle Speed > 10 km/h

Figure 3: Definition of stop&go in RDE-test

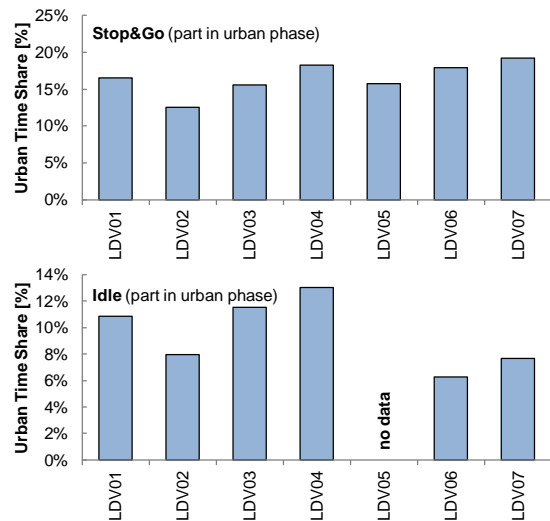
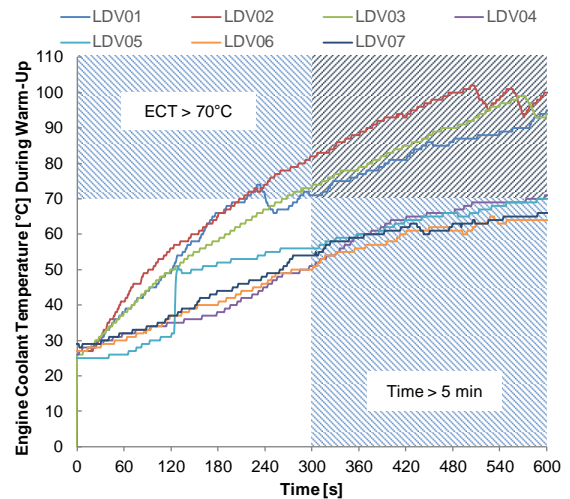


Figure 5: Time courses of the engine coolant temperature during warm-up and time shares of stop&go and idling in the RDE-tests

## Idling

The idling phase is given, when the engine speed is between 500 rpm and 900 rpm and the vehicle speed is below 1 km/h.

Figure 4 shows the definition and example of idling in the urban part and Figure 5 summarizes the shares of idling in the urban part for all investigated vehicles. These shares are in the range of 6% to 13%.

According to these definitions, there is a certain overlapping of the data of the considered non-driving situations, see Figure 6.

## 3. Results

The evaluated emissions data are expressed as total cumulated values in [g], [#], as emissions per time in [g/min], [#min] or as specific emissions per distance [g/km], [#km]. The specific emissions (per km) respond to the legal view, they are comparable with legal limit values, but they are not applicable for the non-driving situations, where the distance driven is zero (like idling or stop&go). These facts are considered in the data representation.

### 3.1. Warm-up

Figure 7 represents the cumulative emissions over time during the urban phase (13.7 km) for the gasoline vehicles. Figure 8 shows the analogous results for Diesel vehicles. It can be remarked that for the gasoline vehicles (LDV1 - LDV3), the ECT 70-warm-up happens earlier or simultaneously with the 5 minutes-point. For the Diesel vehicles (LDV4 - LDV7) inversely, the ECT 70-warm-up takes generally a longer time and it arrives after the 5 minutes-point.

From the comparison of vehicles, it can be stated, that:

vehicles with smaller engine displacement produce lower CO<sub>2</sub>-emissions,

most emissions of CO and NO<sub>x</sub>, especially in the “gasoline” group are produced during and shortly after cold start,

in both vehicles’ groups: “gasoline” and “Diesel”, there are quite considerable emissions differences between the vehicles, resulting mostly from different efficiencies of the exhaust aftertreatment systems,

the urban phase (13.7 km) is driven by different vehicles at different time, due to different average speeds resulting from the traffic situations.

Specific emissions (per km) and their increase factors in the warm-up phase are compared for all vehicles in the Figure 9.

The CO [g/km] in warm-up are generally higher than in the entire urban phase (13.7 km). The “warm-up increase factor” varies between 2 & 11 for gasoline and 1 & 4 for Diesel vehicles. CO-values of LDV4 are particularly high indicating most probably some problems of engine, or of inactive DOC.

The NO<sub>x</sub> [g/km] values of two Diesel vehicles (LDV4 & LDV5) are very high, which particularly signalizes a malfunction of the SCR-system of LDV5 (LDV4 is not equipped with SCR). The specific emissions in warm-up are sometimes higher than in the urban phase with the “increase factor” ranging between 0.9 & 7.5 for gasoline and 0.9 & 5 for Diesel vehicles.

The nanoparticle emissions PN are efficiently eliminated by the DPF’s – all investigated Diesel vehicles were equipped with a filter. In the “gasoline” group, the PN-data were available only for the LDV2, which was equipped with GPF. This GPF enables the urban PN-emission to be reduced below the limit value ( $6 \cdot 10^{11}$  #/km). For the shorter warm-up phases, the emission peak of the cold start gets more weight and the distance driven is shorter. The filtration quality of this GPF, comparing to the DPF’s is quite weak and the high specific PN-emission over the warm-up gets high above the limit value. Similar experiences exist at AFHB from the previous research on GPF’s, [16, 17]: the PN-emissions of a gasoline car (sometimes also with PFI) can reach  $10^{13}$  #/km in WLTC<sub>cold</sub>. The particle count filtration efficiency of the investigated GPF’s could be as low as 70%-80% in WLTC, in opposition to DPF’s. With this knowledge the authors suggest that the non-measured PN-values of the other two gasoline vehicles could be in average of this “urban” phase at least in the range of [ $10^{13}$  #/km].

The PN warm-up increase factors for gasoline vehicle are between 2 & 4 (regarding both definitions of warm-up) and for Diesel vehicles these increase factors are between 1.5 & 10. This means that even the DPF’s with the best filtration quality allow a certain penetration of the cold start PN-emission peak, of course at an absolute very low emission level.

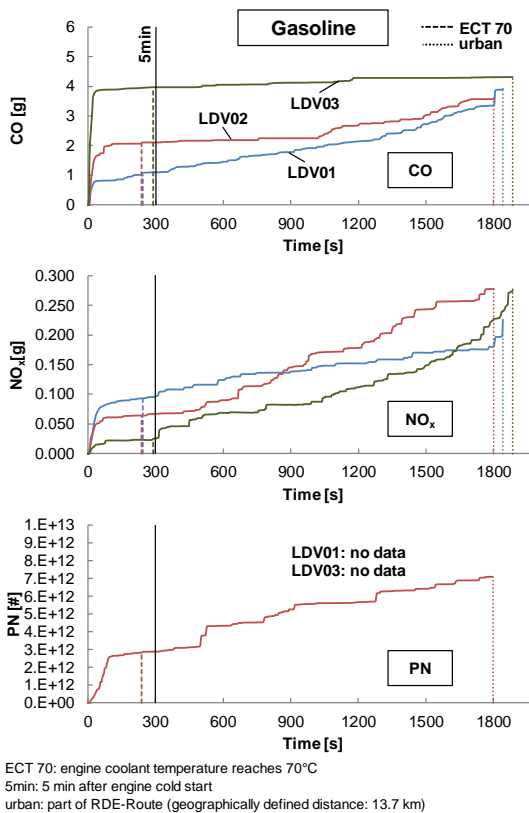


Figure 7: Cumulated emissions of gasoline vehicles during the warm-up phase

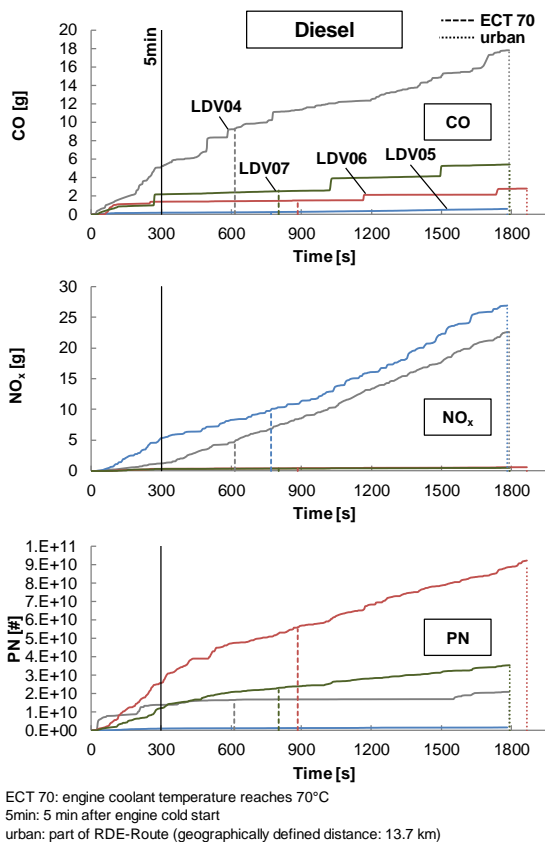


Figure 8: Cumulated emissions of Diesel vehicles during the warm-up phase

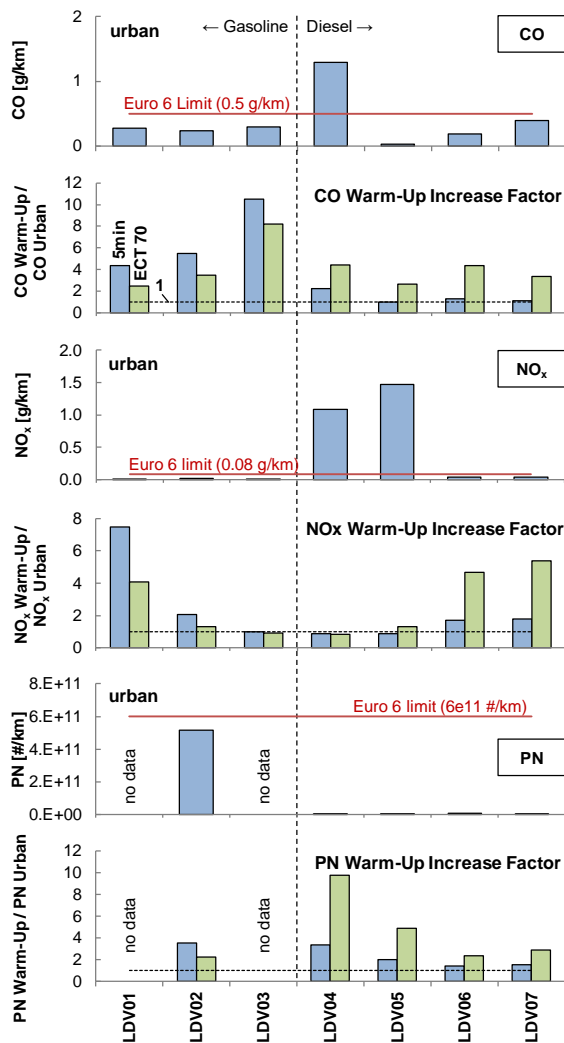


Figure 9: Specific emissions and their increase factors in the warm-up phase

### 3.2. Stop&go

The cumulated emissions in stop&go phases are summarized for all vehicles in [Figure 10](#).

The comparison of emissions of the single vehicles offers a similar picture, as in the previous [Figure 9](#):

- in the “gasoline” group: CO<sub>2</sub>-emission is higher for bigger engines (engine swept volume increases from LDV1 to LDV3); CO-value is the highest for LDV3, which shows the slowest warm-up (see [Figure 5](#)); the PN-values are only given for LDV2 (equipped with GPF) and they confirm the mediocre filtration quality comparing to DPF’s.
- in the “Diesel” group: high CO for LDV4 (insufficiency of engine, or of DOC); high NO<sub>x</sub> for LDV4 (no SCR) and for LDV5 (inadequacy of SCR); near-to-zero PN-emissions, thanks to right-quality DPF’s.

An interesting finding is given by the higher CO- and NO<sub>x</sub>-emissions of LDV7 relatively to LDV6. Both vehicles have the same engine displacement volume and nearly identical exhaust aftertreatment systems (DOC, DPF, SCR). LDV7 was driven with its start-stop-control switched on.

This means that during the stop&go operation, the engine was stopped and started independently on the drivers wish. By engine stop, there are no emissions produced, but by engine start, there is always an emission peak. The balance between the emission saving and emission over-producing depends on how long is the stop-time and how intense is the start-peak. The last one depends strongly on the thermal condition of the engine and of the exhaust system. In the present urban part (first 13.7 km) several start-stops must have been performed with not entirely warm exhaust aftertreatment system and the higher emission peaks at engine restart overweighed the emissions results of LDV7.

Relatively to the urban part (13.7 km) the cumulated emissions in stop&go are increased / decreased by the following factors:

for gasoline vehicles:

CO 2 - 6  
 NO<sub>x</sub> 0.7 -2.5  
 PN 1.7 (1 vehicle)  
 CO<sub>2</sub> 0.5 - 0.7

for Diesel vehicles:

CO 0.2 - 2.2  
 NO<sub>x</sub> 0.1 - 0.4  
 PN 0.4 - 2.3  
 CO<sub>2</sub> 0.3 - 0.6

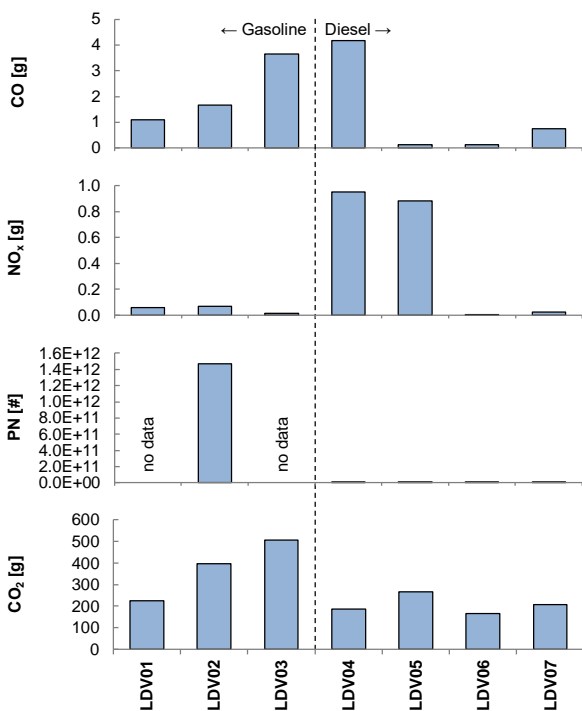


Figure 10: Cumulated emissions in stop&go

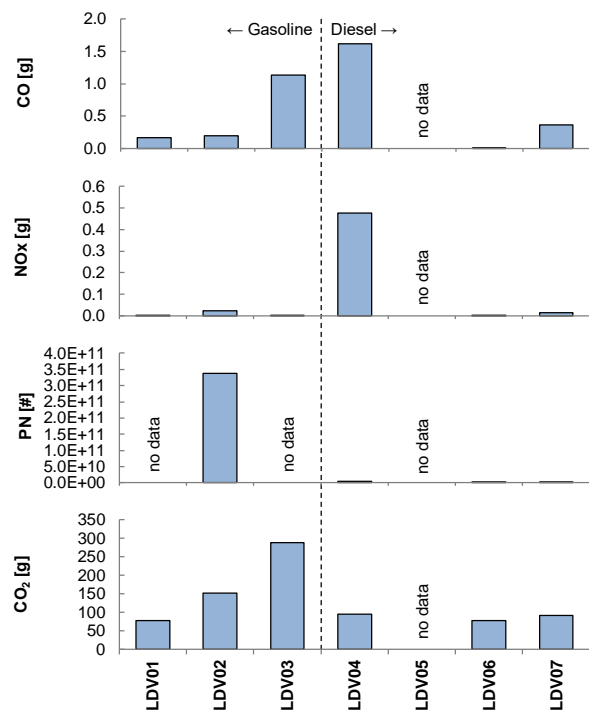


Figure 11: Cumulated emissions at idling

### 3.3. Idling

Figure 11 represents the cumulated emissions at idling for all investigated vehicles. The relationships between the vehicles and the technical explanations are similar as in the previous section for “stop&go”.

Relatively to the urban part (13.7 km) the cumulated emissions at idling are mostly decreased with the following factors:

for gasoline vehicles:

CO 0.5 - 2.5  
 NO<sub>x</sub> 0.3 - 1.1  
 PN 0.7 (1 vehicle)  
 CO<sub>2</sub> 0.3 - 0.6

for Diesel vehicles:

CO 0.1 - 0.9  
 NO<sub>x</sub> 0.1 - 0.4  
 PN 0.5 - 1.8  
 CO<sub>2</sub> 0.3 - 0.4

## 4. Reproduction of non-driving situations

The tests were performed on chassis dynamometer with two gasoline and two Diesel passenger cars. The simulated driving situations were:

- Cold start (at 20-25°C) and warm-up phase with different load after start (15 km/h and 80 km/h).
- Stop&go operation with different portions of idling.

The vehicles of each group represented a newer and an older technology.

In the gasoline group, the newer (modern) vehicle is equipped with the engine and exhaust aftertreatment technology Euro 5 (with GDI, TWC) and the older vehicle (dated) responds to the emission class Euro 3 (with MPI, TWC).

As the most interesting findings can be mentioned:

- the emissions of CO, HC, NO<sub>x</sub> and PN are generally higher for the older vehicle and, for both vehicles, these emissions are higher with higher load in the warm-up phase,
- the majority of these emissions is cumulated in the first 0.5 km of distance approximately,
- the PN-emissions of the dated vehicle (MPI) at high load are identical with the emissions of the modern vehicle (GDI); this confirms the high PN-emissions potential of the MPI fleet as well.

In the Diesel group, the modern vehicle means Euro 6 (DOC, DPF, SCR) and the older (dated) means Euro 2 (DOC).

Some remarkable findings are:

- the emissions of CO, HC, NO<sub>x</sub> and PN are generally higher for the older vehicle, the emissions of CO, HC, and for the older vehicle, also NO<sub>x</sub>, are higher with lower load (inversely to gasoline vehicles),
- the emissions of CO, HC and NO<sub>x</sub> for the older vehicle, and particularly at low load, are cumulated not only at cold start but also in the entire represented time slot until 4 km distance driven,
- the PN-emissions of both vehicles are cumulated mainly during the cold start; for the older vehicle they are significantly higher than for the newer one (up to 6 orders of magnitude) and are independent of the load.

The tests of the stop&go operation with varying portion of idling were performed with warm engine and warm exhaust aftertreatment system. As a consequence, the measured emission values were very low. The exception is the older Diesel vehicle, which was equipped with a quite aged DOC only. The higher emissions which result from this vehicle allow to remark much better the effects of the idling rate.

The answer to the question: how does the share of idling influence the emissions in the stop&go operation? – finally depends on the representation (consideration) over the distance or over the time. With increasing portion of idling the distance-specific emissions (per km) increase and the time-specific emissions (per min) decrease.

## 5. Conclusions

### 5.1. Analysis of present data

For research of emissions from non-driving or special driving situations the RDE data of 7 vehicles (3 gasoline and 4 Diesel) were analyzed.

The first 13.7 km of distance after cold start were defined as “urban” part and definitions of: warm-up (including start), “stop&go” and idling, were established in order to enable the automatic evaluation.

The most important conclusions from this research are:

- the emissions of CO, NO<sub>x</sub> and PN are in the cold start and in the first part of the warm-up phase (c.a. 25s) considerably higher, than in the rest of the investigated urban phase, (HC-data were not available),
- the special emitting situations: “stop&go” and idling are frequently given during the warm-up phase, i.e. with engine and exhaust treatment system not warm enough,
- vehicles with smaller engine displacement have lower cumulated CO<sub>2</sub>-emissions (lower fuel consumption), they are tendentially quicker to be warmed-up,
- in both vehicles’ groups: “gasoline” and “Diesel” there are quite considerable emissions differences between the vehicles, resulting mostly from different efficiencies of the exhaust aftertreatment systems,
- the specific emissions [in g/km] are in the warm-up generally significantly higher than in the investigated urban phase (13.7 km); the respective “increase factors” are in average: for CO 6; for NO<sub>x</sub> 4; for PN 6,
- the GPF, which was applied on one of the investigated gasoline vehicles showed a weak filtration quality comparing to the DPF’s which were used on the Diesel vehicles,
- the start-stop-system switched on during the warm-up is tendentially disadvantageous because the cold exhaust aftertreatment system cannot eliminate sufficiently the emissions peaks produced by restarting the engine.



## 5.2. Reproduction of non-driving situations

The non-driving (or special driving) situations – warm-up with different engine load and stop&go with different portions of idling – were reproduced on a chassis dynamometer with two gasoline vehicles and two Diesel vehicles. Both vehicles types were represented by a newer and an older technology.

During the cold start and warm-up in the first 2.5 km, the emissions of older type vehicles are generally higher than for the newer technology. The majority of emissions are accumulated in the first 0.5 km of the distance driven.

The PN-level of older technology gasoline vehicle (MPI) at higher load (80 km/h) is equal to the PN-level of the newer technology (GDI) – both vehicles without GPF.

The advantages and the efficiency of the modern Diesel aftertreatment (DPF) are confirmed by a significant reduction of PN.

In the stop&go operation, there are several tendencies of increasing the specific emissions [mg/km] with the higher share of idling (except of: HC for gasoline vehicles and PN for all vehicles). One of the factors taken into consideration is the shorter distance driven with the higher portion of idling in the tested time interval. The consideration of emissions per time [mg/min] results in lowering most of the emissions with higher portion of idling.

### Acknowledgement

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## 7. Abbreviations

AFHB	Abgasprüfstelle FH Biel, CH
ASTRA	Federal Office of Roads
CF	Conformity Factor
CLD	Chemoluminescence Detector
DI	Direct Injection
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particle Filter
ECT	engine coolant temperature
EFM	Exhaust Flow Meter
EMPA	Eidgenössische Material-Prüfanstalt
EMROAD	Data processing reference software
EOT	engine oil temperature
ES	engine start
EU	European Union
FID	Flame Ionization Detector
FOEN	Federal Office of Environment, CH
GPF	Gasoline particulate filter
GPS	Global Positioning System
HD	Heavy Duty
HDV	Heavy Duty Vehicles
ISC	In-Service Conformity
LD	Light Duty
LDV	Light Duty Vehicles
NDIR	Non-Dispersive Infrared
OBD	On Board Diagnosis
OCE	Off-Cycle Emissions
PEMS	Portable Emissions measurement system
PFI	port fuel injection
PN	Particle Number
RDE	Real Driving Emission
ResRDE	research of RDE
SCR	Selective Catalytic Reduction
TA	Type Approval
TPA	Tailpipe Attachment
TWC	Three-way catalyst
V	vehicle
WHTC	World Heavy-Duty Transient Cycle
WLTC	World Light-Duty Transient Cycle