SETUP FOR EMISSIONS REDUCTION TESTING OF BUS/COMMERCIAL VEHICLE BRAKES ON A DYNAMOMETER

WP2

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LIST OF ABBREVIATIONS

ACRONYM	DESCRIPTION
VMAX	LINK Vehicle Measurement and Data Acquisiton System
CDF	Cumulative Density Function
AUVASA	Autobuses Urbanos de Valladolid, S. A.
IUTA	Institut für Umwelt & Energie, Technik & Analytik e.V.
M+H	Mann + Hummel International GmbH & Co. KG
ZF	ZF Friedrichshafen AG

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
a	Acceleration in m/s²
t	Time in s
T	Temperature in °C
v	Velocity in km/h

PUBLISHABLE SUMMARY

Brake Wear Particles have a significant contribution to traffic related particulate mass emissions in urban environments. Particulate mass in the ambient air is related to several health issues, and therefore a reduction of particulate mass in the ambient air is of interest. Retrofit Brake Emission Filters for city buses are a possible solution to address this issue. The contribution of city buses to brake wear particulate matter in the ambient air is not quantified yet. Emission measurements on a dynamometer are the state-of-the-art method to quantify emission factors. A measurement method for passenger cars is available but a measurement method for commercial vehicles needs to be developed, including the testing protocol. The development of a testing protocol is required. The above-mentioned point is the subject of Task 2.2. The results are of interest to make a measurement procedure for commercial vehicle's brake wear emissions available, and also to understand the contribution of city buses to brake wear particulate matter in ambient air.

1. INTRODUCTION

In the previous technical report, the development of the driving cycles for Valladolid and Ancona was described, based on measurements taken in these cities. These driving cycles were reviewed with the involved partner in regular meetings and will be used by Link and IUTA in Tasks 2.2 and 2.4 for performing brake dust emission measurements on a dynamometer test rig.

During this period, LINK developed and built the experimental emission setup and conducted the first validation measurements. The brake dynamometer, test setup and testing protocol are described in this report.

2. OBJECTIVES AND EXPECTED IMPACT

2.1.OBJECTIVES

Task 2.1: The goal was to onboard the new partner LPP and conduct bus measurements in Ljubljana. Based on the measurements in Valladolid and Ancona, the related drive cycles needed to be created.

Task 2.2: The main objective was to set up a measurement setup for the new dynamometer and complete the baseline emission measurements.

3. DESCRIPTION OF TECHNICAL/SCIENTIFIC ACTIVITIES

Figure 1 shows the electropolished, stainless steel emission enclosure. It features smooth transition angles at the inlet and outlet sides and is designed similarly to the enclosure requirements described in GTR24, but is larger to accommodate bigger brakes. On the left side of Figure 1, the sampling duct with a 200 mm diameter is shown, along with the sample elbow with probes for aerosol sampling. On the right side (background of Figure 1), the HEPA box for inlet air filtration is visible, ensuring a low background concentration inside the enclosure and sampling tunnel.

Figure 1: Brake enclosure for emission measurements on the CV dynamometer

A detailed view of the emission enclosure is shown in Figure 2. On the right side, the brake assembly inside the enclosure is visible. The enclosure is designed to allow filter devices to be installed without taking up too much space, still permitting airflow around them.

Figure 2: Detailed view on the emission enclosure with sample duct (left) and brake assembly (right)

The measurement devices used for emission measurement are shown in Figure 3. There are three carts equipped with measurement devices:

- M4222 PN (Figure 4 center): A system with two condensation particle counters, dilution stages, and a catalytic stripper. It measures total and solid particle numbers according to GTR 24.
- M4222 PM (Figure 4 left and right): A system consisting of two carts for measuring PM10 and PM2.5. The sampling flow is controlled by pumps that draw air through filters for gravimetric

measurements. The system includes an automated filter changer for robust and automated measurement processes.

Figure 3: Experimental setup for commercial vehicle brake emission measurements consisting of the dynamometer, brake enclosure, sample duct, sample elbow, devices for measurement of particle number (total and solid), particle mass (PM2.5 and PM 10).

Figure 4: LINK emission measurement system M4222 PM (left and right) and M4222 PN (center) for measurement of particle number (total and solid), particle mass (PM2.5 and PM 10).

An essential part of the sampling system for particle mass are the cyclones, which separate the aerosol into particles larger than PM10/PM2.5 and those that are part of PM10/PM2.5. The cyclones are positioned before the gravimetric filters in the direction of the sampling flow. They can be seen in Figure 5, attached to the sampling elbow. This figure also shows the control display for the particle number measurement system, summarizing all status and measurement information and allowing automated leakage checks. The functionality of the automated filter changer is shown in Figure 6. The filter has three main positions:

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- Filter magazine for new filters
- Sampling position
- Filter magazine for used filters

Figure 5: Emission Enclosure with sample elbow, PM cyclones, sampling tubes and control display for the M4222-PN

Before the test, new weighed filters are inserted in the magazine for new filters. As soon as the emission cycle on the dynamometer starts, a new filter is automatically switched into sampling position and a controlled sampling air flow is pumped through the filter. After the end of the cycle, the used filter is automatically switched into the magazine for used filters and is ready for final weighing.

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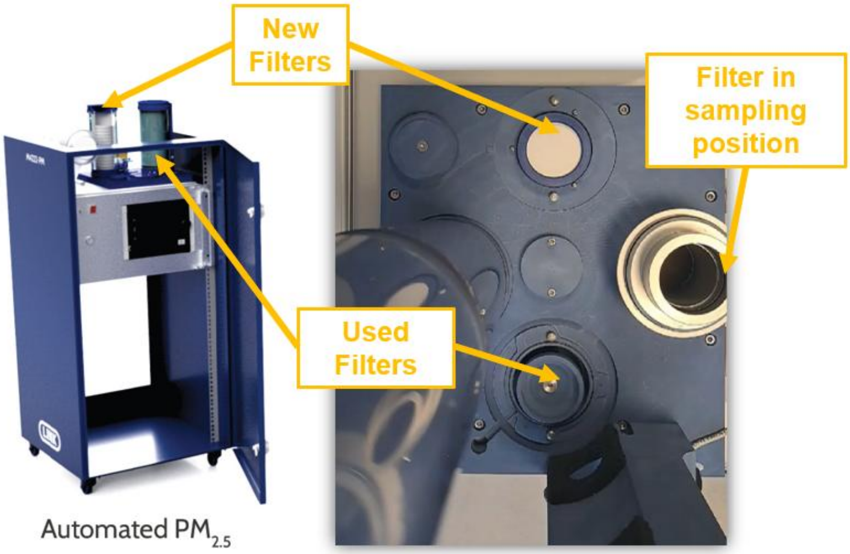

Figure 6: LINK emission measurement system M4222 PM with detailed view on magazine for new filters, used filter and sampling position.

3.1.1. TASK 2.2

The task 2.2 is a closed cooperation between Link who has the lead of this task and IUTA, supporting with measurements equipment and know how. Testing protocols have been developed. Several tests have been conducted together at Link's new dynamometer test rig to obtain the baseline for emissions of bus brakes without brake dust filter. These measurements were delayed due to the late delivery of the dynamometer test rig.

The measurements were conducted using a suite of measurement instruments, including an electrical mobility spectrometer and an optical aerosol spectrometer to obtain number size distributions in a wide size range from approximately 5 nm to 10 µm, a condensation particle counter to obtain the total number concentration of emitted particles as well as filter samplers for PM2.5 and PM10 to obtain the total mass of the emitted particles.

In the previous technical report, the development of the cycles was described. Figure 7 shows the cycle for Valladolid C1. This cycle consists of continuous speed profiles with continuous change in acceleration from every second to the next second (1 Hz data).

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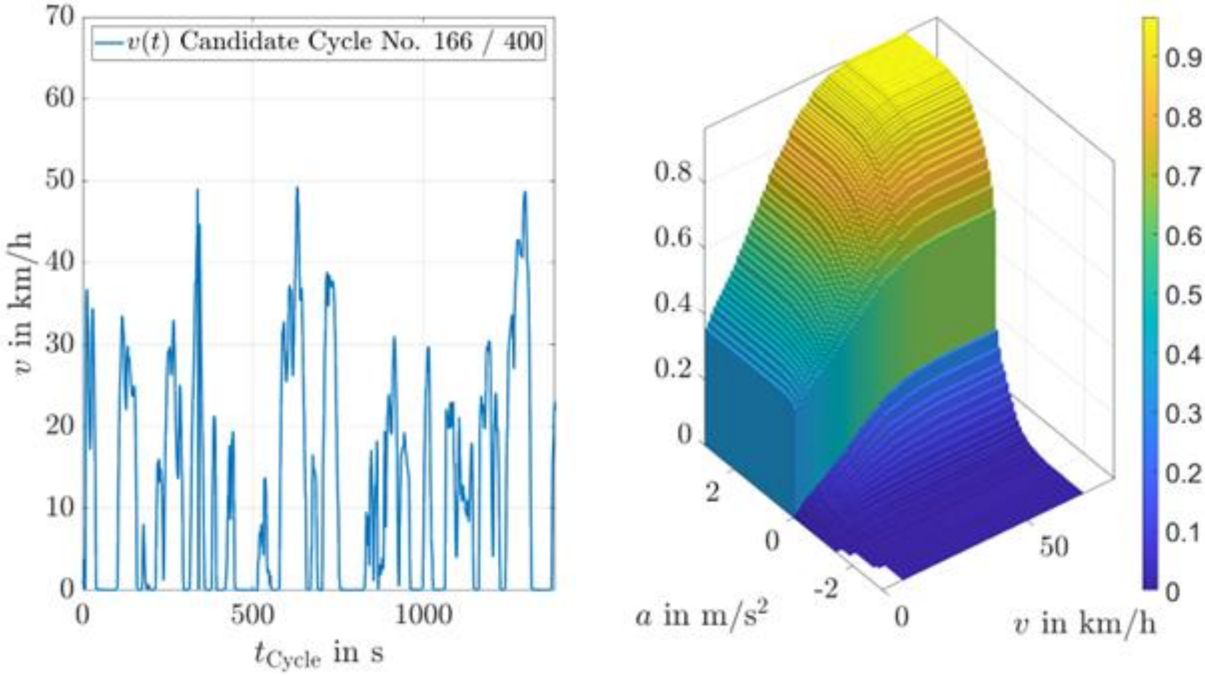

Figure 7: Velocity time series for candidate cycle 166 from 400 cycles for Valladolid Bus Line C1 (left) and cumulative density function for velocity and acceleration of this candidate cycle (right) according to the new method with extended short trips and larger time intervals for short trip duration selection

To transfer this speed profile to a profile with piecewise linear speed traces (constant acceleration for every piece, acceleration limits were defined to differentiate between:

- High acceleration (conducted with electric engine from the dynamometer)
- Low acceleration (conducted with electric engine from the dynamometer)
- Low deceleration (conducted with electric engine from the dynamometer)
- High deceleration (conducted with friction brake)

This separation is shown in Figure 8 for one acceleration, coasting, and brake event.

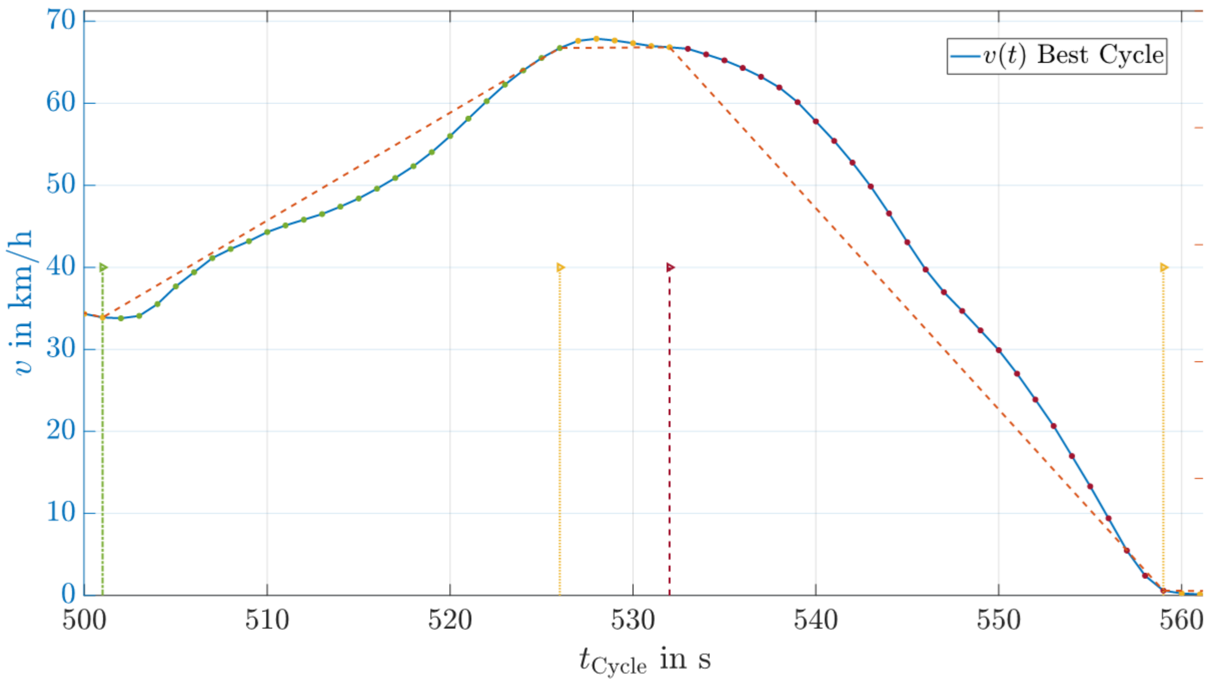

Figure 8: Velocity time series of an acceleration event and brake event within the Valladolid C1 cycle: original cycle (blue line), piecewise linear cycle (orange line), start of acceleration event (green line), start of coasting (yellow line), start of brake event (red line).

To translate this speed profile into a dynamometer control code, a Matalb tool was written that automatically exports a excel file. The excel file can be imported into the dynamometer control program (Figure 9 and Figure 10).

```
%% Track-Sim-Array schreiben

n_Dec = 2;

j = 3;

for i = 1:length(Pcw_Flag)

    % Acceleration & Coast
    if (Pcw_Flag(i) == 1 || Pcw_Flag(i) == 2) == 1

        TS_Step{j} = j;
        TS_Action{j} = 'Do_Set_Step_Setpoints';
        TS_CycleTime{j} = 0;
        TS_Brk_Speed{j} = fix(v_Cycle_Pcw(i) * 10^n_Dec)/10^n_Dec;
        TS_Rel_Speed{j} = 0;
        TS_Drive_Accel_Time{j} = t_Cycle_Pcw(i+1)-t_Cycle_Pcw(i);
        TS_Devel_Level{j} = 0;

        j = j + 1;

        TS_Step{j} = j;
        TS_Action{j} = 'Do_Drive_On_Drv_Spd';
        TS_CycleTime{j} = t_Cycle_Pcw(i);
        TS_Brk_Speed{j} = fix(v_Cycle_Pcw(i) * 10^n_Dec)/10^n_Dec;
        TS_Rel_Speed{j} = 0;
        TS_Drive_Accel_Time{j} = t_Cycle_Pcw(i+1)-t_Cycle_Pcw(i);
        TS_Devel_Level{j} = 0;

        j = j + 1;

    % Coast
    elseif Pcw_Flag(i) == 2

    % Brake
    elseif Pcw_Flag(i) == 3

        TS_Step{j} = j;
        TS_Action{j} = 'Do_Set_Step_Setpoints';
        TS_CycleTime{j} = 0;
        TS_Brk_Speed{j} = fix(v_Cycle_Pcw(i) * 10^n_Dec)/10^n_Dec;
        TS_Rel_Speed{j} = fix(v_Cycle_Pcw(i+1) * 10^n_Dec)/10^n_Dec;
        TS_Drive_Accel_Time{j} = 0;
        TS_Devel_Level{j} = fix(((v_Cycle_Pcw(i+1)-v_Cycle_Pcw(i))/3.6)/(t_Cycle_Pcw(i+1)-t_Cycle_Pcw(i)) * 10^n_Dec)/10^n_De
```

Figure 9: Matlab code for the automated generation of the TrackSim control program

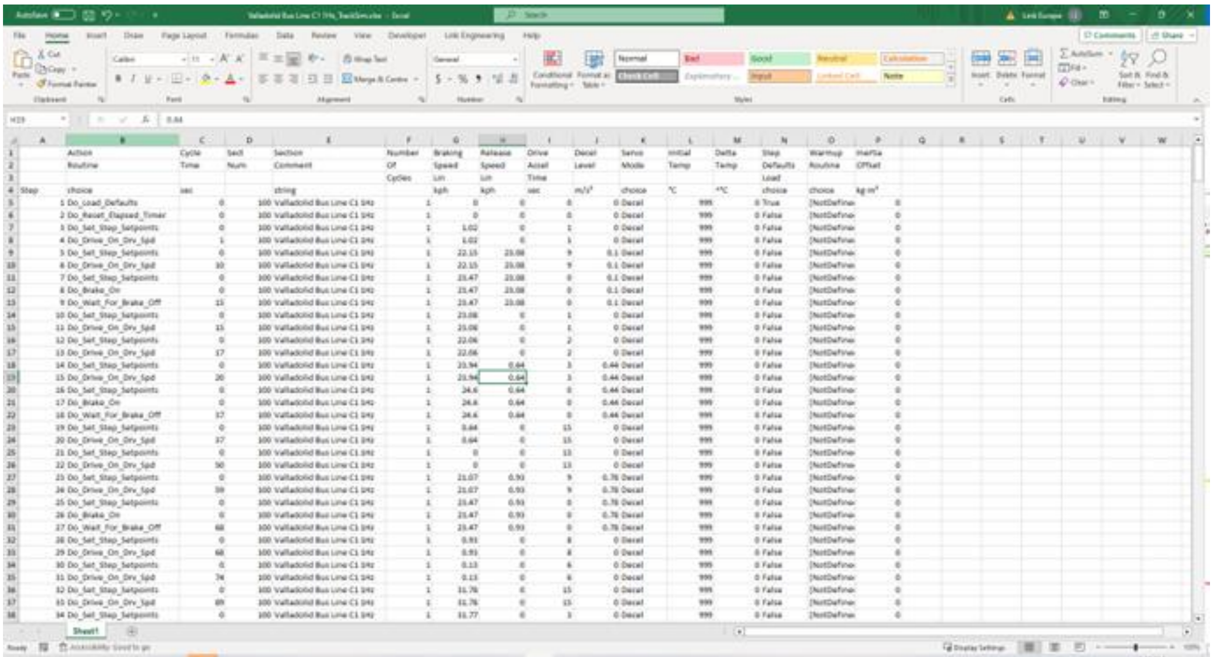

Figure 10: TrackSim-commands in Excel, generated from Matlab tool

4. RESULTS AND DISCUSSION

With this control program the first validation measurements were conducted by LINK on the LINK CV dynamometer. The speed (green) and brake disc temperature (red) time series are shown in Figure 11 for the Valladolid cycle (consisting of the bus line cycles C1, 2 and 3). An additional particle number concentration is shown in Figure 12)

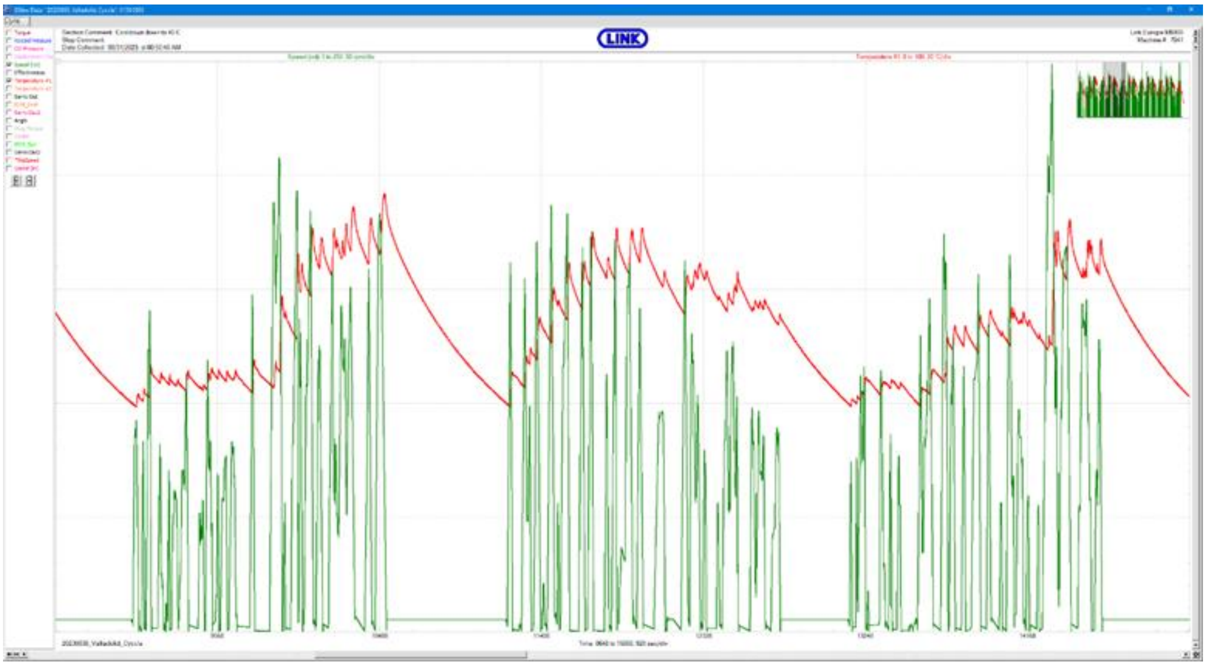

Figure 11: Speed (green) and temperature (red) time series of the Valladolid cycle (C1, 2 , 3)

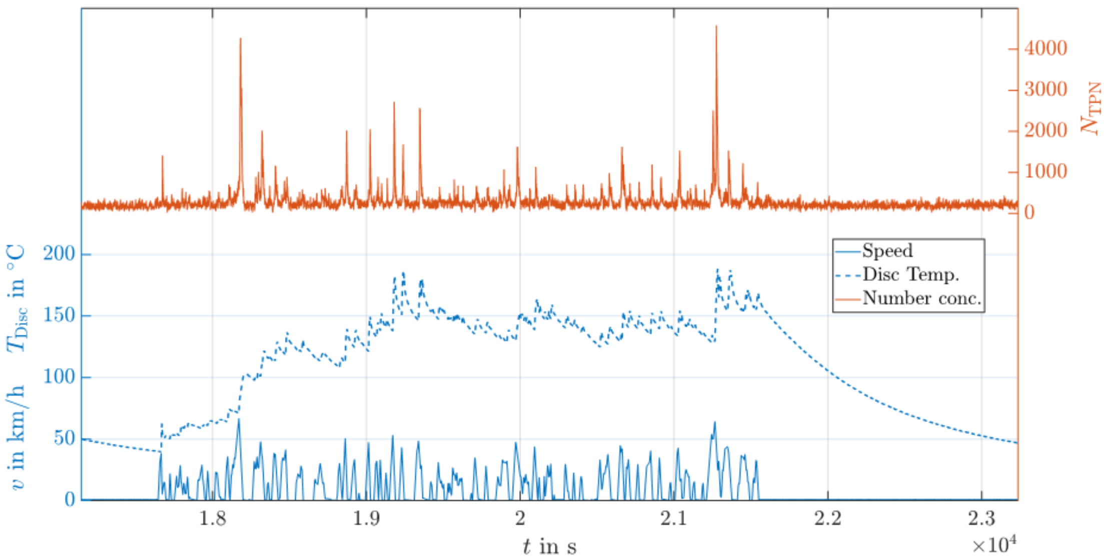

Figure 12: Speed (solid blue line) and disc temperature (dotted blue line) and particle number concentration (red) as time series

In the CDF plots below (Figure 13) the disc temperatures for bus and dynamometer (dyno) measurements are compared.

For the bus measurement, the sliding disc temperature was recorded. Results showed an average temperature of 80°C with peaks reaching 130°C. In contrast, the dyno measurement focused on the embedded disc temperature, yielding higher readings with an average temperature of 125°C and a maximum of 180°C.

These differences highlight the need to account for driving resistances and the use of the retarder in evaluating braking performance. These factors can significantly influence the temperature profile of the braking system, especially under dynamic conditions.

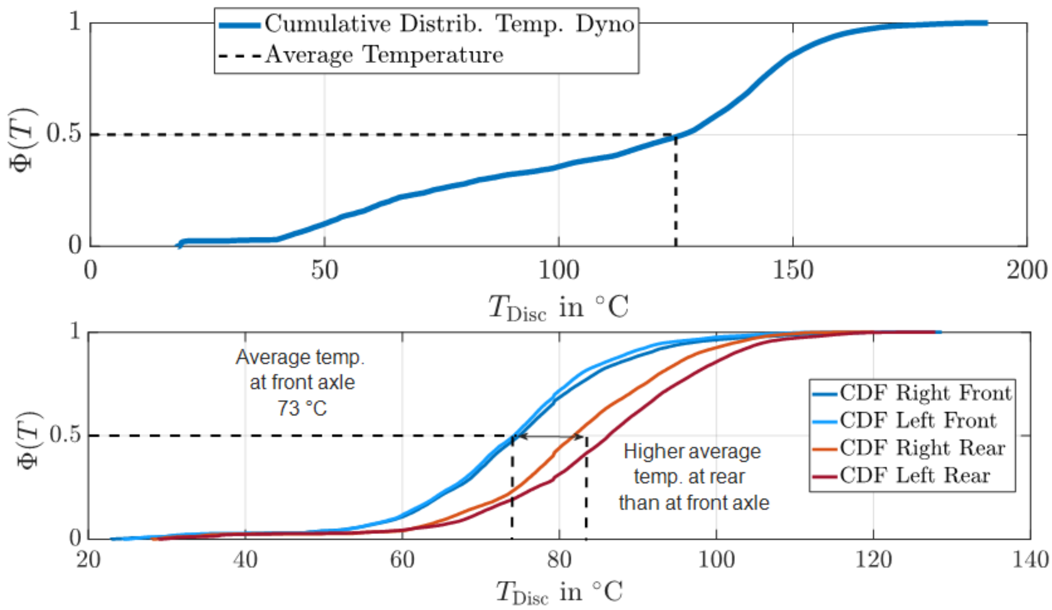

Figure 13: CDF plots

All emission results (Figure 14) presented below were gathered after bedding was completed to ensure accurate assessments of particulate emissions.

Following bedding, the PM10 emission factor (EF) recorded on the dynamometer was 60 mg/km, while the particle number (PN) emission factor was measured at 3.5×10^{10} particles per km.

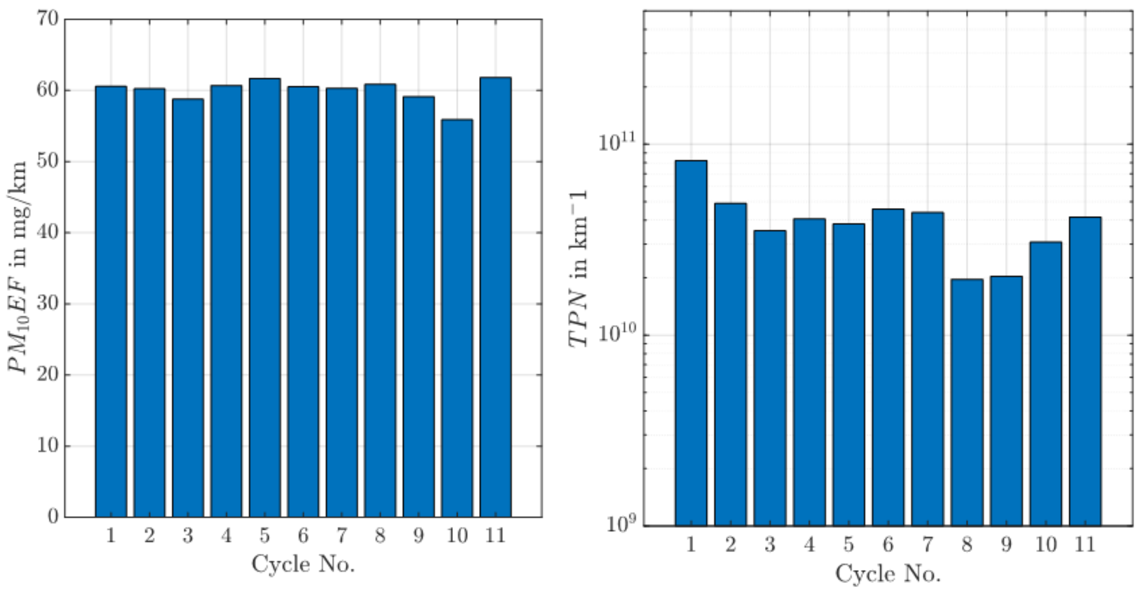

Figure 14: Emission results

In the following the measured PM10 emission factors are compared to an estimation based on the measured pad wear. The estimation of PM10 emission factors (EF) was conducted based on measured pad wear data obtained from the bus, along with several assumptions regarding wear and emissions. The calculated PM10 EF from this approach is 38.54 mg/km (Figure 15).

This estimated PM10 EF value was compared to the measured PM10 EF at the dynamometer, which was 60 mg/km. The difference between the estimated and measured values suggests that the assumptions made in the calculation, while rough, provide a reasonable approximation. The lower estimated value on the bus, compared to the dyno measurement, may result from additional factors that are present in real-world driving but not yet simulated in the dynamometer setup.

Furthermore, decreases in both temperature and emission factors are expected when driving resistances are implemented on the dynamometer. Introducing these resistances will better simulate real-world conditions, likely leading to a closer alignment between measured and estimated PM10 emissions. This adjustment should bring the dynamometer values down, possibly aligning more closely with the bus-based estimation of 38.54 mg/km, making the estimation plausible under modified test conditions.

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```
%% Estimation of PM10 Emission Factor based on measured Pad wear in bus

% Distance in km
s = 326.9312;

% Average wear of pads Front Axle  in g
Avg_Wear_Pads = mean([9.9, 10, 9.9, 12.2]);
% 2 Pads per Brake
Wear_Pads = 2 * Avg_Wear_Pads;

% Ratio Wear Pad / Wear Disc
Ratio_Wear_Pad_Disc = 1;
% Ratio PM10 / Wear
Ratio_PM10_Wear = 0.3;

% Emission Factors in mg/km
EF_Wear = (Wear_Pads * (1+1/Ratio_Wear_Pad_Disc) ) / s * 10^3;
EF_PM10 = EF_Wear * Ratio_PM10_Wear;
```

```
EF_Wear =

  128.4674


EF_PM10 =

   38.5402
```

Figure 15: Calculated PM10 EF

5. LINKS WITH OTHER WPS

The dynamometer test protocol from this Task 2.2 will be used in Task 2.4 for the measurement of the reduction potential of the brake dust filter.

6. CONCLUSIONS AND RECOMMENDATIONS

This report outlines the progress made in developing and applying methodologies for the measurement and estimation of brake emissions in commercial vehicles under both controlled and real-world conditions. The work involved onboard bus measurements, dynamometer testing, and the creation of driving cycles tailored to cities such as Valladolid, Ancona, and Ljubljana.

Dynamometer testing facilitated controlled analysis of particulate emissions, including PM10 and particle numbers (PN). Discrepancies between measured and estimated PM10 emission factors were noted. For example, while dynamometer testing indicated a PM10 emission factor of 60 mg/km, estimations based on brake pad wear produced a lower value of 38.54 mg/km. This divergence highlights the need for refined assumptions and better simulation of real-world conditions, such as driving resistances and retarder usage, which will be incorporated in subsequent tests.

Bus measurements conducted in Ljubljana utilized CAN data extraction with the aid of a dbc file, enabling detailed data collection for both hybrid and diesel buses. These measurements form the foundation for developing a Ljubljana-specific driving cycle, which will be used for emission factor testing on the dynamometer under controlled conditions.

The evaluation of brake dust filter efficiency has not been concluded as part of this task. This investigation will be addressed in **Task 2.4**, where further analysis and validation will be carried out under standardized testing protocols.

Moving forward, the focus will be on completing the development of driving cycles, implementing driving resistances on the dynamometer, and analyzing the influence of retarder use. These steps are essential for improving the accuracy and reliability of brake emission factor measurements and ensuring their applicability to real-world vehicle operations.