# Laboratory and Field Measurements of Solid Particle Number with the Nanoparticle Emission Tester (NPET)


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## Introduction and Motivation

The introduction of **diesel particulate filters (DPF)** lead to a significant reduction of exhaust emissions. When operating properly they reduce **particulate matter (PM)** by more than 99%. Yet existing field-based methods to measure engine PM emissions were typically opacity based and not sensitive enough to measure the greatly reduced particle concentrations downstream of a DPF (Mayer et al., 2004). For that reason solid particle number concentration measurement has become a proven metric to determine compliance with corresponding emissions limits such as Euro 5b/6 standards (Bischof, 2015). More recently Switzerland was the first country worldwide to introduce legislation aimed at in-use compliance testing of construction machinery DPFs, which also relies on solid particle number **(SR 941.242)**.

## Instrument Configuration

The **Nanoparticle Emission Tester (NPET, Model 3795, TSI Inc.)** a portable, rugged and field usable instrument for measuring the total number of solid particles was first introduced at the 18th ETH conference one year ago (Horn et al., 2014).
It consists of four main elements: (1) a **Sampling Probe** and **Pre-Conditioner**, (2) a **Diluter** that dilutes the raw exhaust at a ratio of 10:1 to cool the sample while preventing condensation, (3) a **Catalytic Stripper** that evaporates and oxidizes semi-volatile material, preventing it from re-condensing into particles, and (4) a **Condensation Particle Counter (CPC)** that individually counts all remaining solid particles. The resulting dilution-corrected concentration is output to the PC or tablet computer that is used to control the NPET.

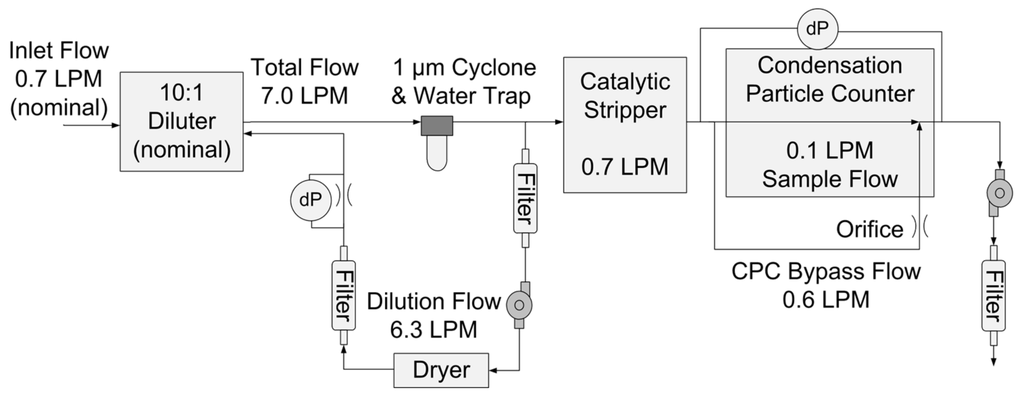


Fig. 1: Operating principle of the Nanoparticle Emission Tester (NPET).

## Performance Characterization: Laboratory and Initial Testing

The NPET's **detection efficiency** was tested in the laboratory using soot generated by a polydisperse combustion aerosol standard (CAST) with geometric standard deviation (GSD) < 1.75. The concentration was determined by a reference CPC (Model 3775, TSI Inc.). The resulting efficiency is shown in Figure 2.

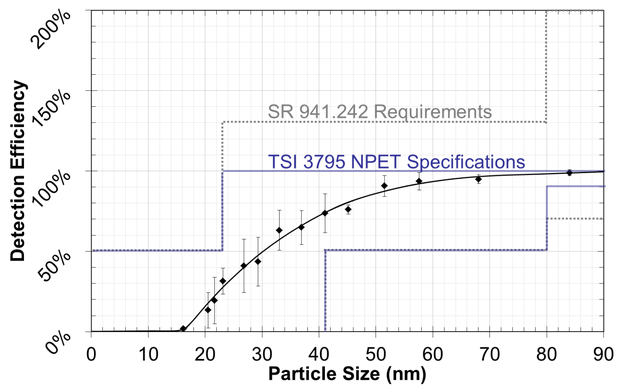


Fig. 2: Detection efficiency of the NPET system using polydisperse CAST generated soot.

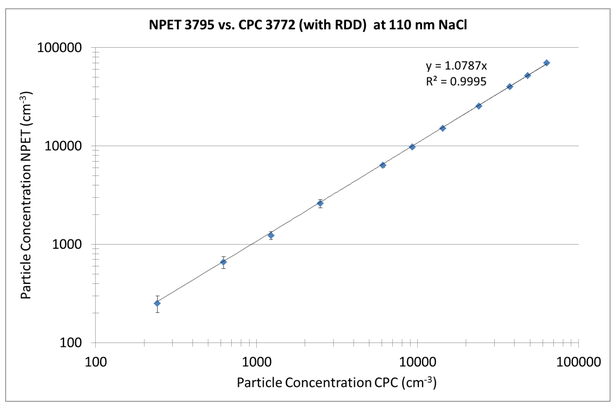


Fig. 3: Linearity of NPET 3795 versus CPC 3772 for monodisperse salt aerosol.

Figure 3 shows the **concentration linearity** of NPET compared to a CPC (Model 3772, TSI Inc.). Salt aerosol (NaCl) was pre-classified to a monodisperse aerosol with a mode diameter at 110 nm. This test aerosol was subsequently diluted at a ratio of 60:1in a Rotating Disk Diluter (Model 379020A, TSI Inc.) operated at 80°C.

For initial tests, NPET and an opacimeter were used to sample DPF filtered exhaust from an Atlas excavator. Figure 4 shows that NPET solid particle concentration and engine speed track very well. The opacimeter was below its lower detection limit downstream of the DPF and no correlation between engine speed and exhaust opacity could be determined.

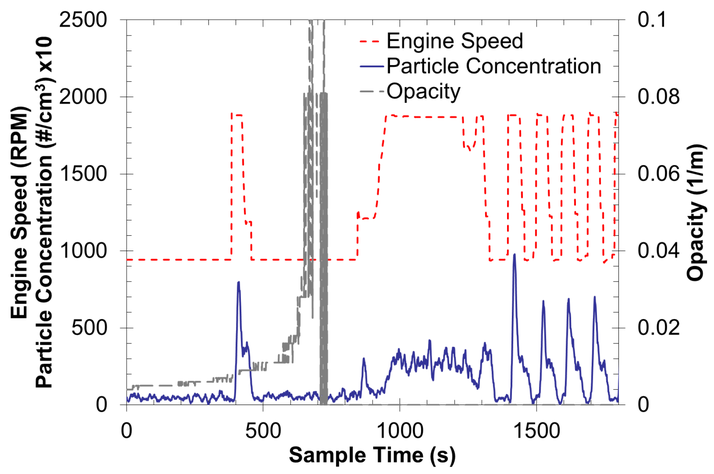


Fig. 4: Solid particle number and opacity measurements of an Atlas excavator (with DPF).

## Testing of DPFs in the Field

### DPF Testing in Chile

Air pollution is a major problem in Santiago, Chile. In 2004 a DPF project in Chile started that includes fleet update of new buses with DFP and a retrofit program. Data from NPET measurements at 10 in-use buses made in the official Swiss Mode either as on-route testing or at the terminal are shown in Figure 6 and Table 1.

In a next step 400 buses will be measured with NPET to check their DPF performance.


4/9/2015 9:20:04 AM

| | | | |
|---|---|---|---|
| Model: | 3795 | Manufacturer: | TSI Inc. |
| Serial: | 3795151101 | Last Calibration: | 2015-03-13 |
| Firmware Version: | 1.1 | Application Version: | 1.1.0.0 |
| Application Key: | 94DC-02B0-9588-C3B3-0D8C-BF52-5E7B-B5C5 | | |

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TSI

**OFFICIAL MEASUREMENT**

| | | | |
|---|---|---|---|
| Date/Time: | 2015-04-09, 09:19:23 | Mean #1 (1/cm³): | 3.99E4 |
| Duration: | 00:00:40 | Mean #2 (1/cm³): | 4.20E4 |
| Operator: | ASA | Mean #3 (1/cm³): | 4.26E4 |
| Machine Make: | verde | Overall Mean (1/cm³): | 4.15E4 |
| Machine Model: | verde | Limit (1/cm³): | 2.5E5 |
| Machine Id: | bjfy74 | Result: | PASS |
| Engine Id: | x | | |

*Ambient Conditions: 23.8 °C, 95.2 kPa, 42 %RH*

SIGNATURE:

Fig. 6: Photos and exemplary test result from first NPET measurements on in-use buses in Santiago, Chile.

Tab. 1: Results from 10 different bus measurement tests with NPET (using official Swiss mode) and Opacimeter in parallel.

| | NPET Official measurement (at idle) | | | | | Opacimeter official measurement (free acceleration) | | |
|---|---|---|---|---|---|---|---|---|
| Bus ID number | NPET measurement 1 | NPET measurement 2 | NPET measurement 3 | NPET total measurement | Pass/Fail Limit=2.5E5 cm$^{-3}$ | Opacimeter measurement 1 | Opacimeter measurement 2 | Pass/Fail Limit=0.24 m$^{-1}$ |
| On route | | | | | | | | |
| BDXR54 | 1.62E+04 | 1.75E+04 | 1.81E+04 | 1.72E+04 | PASS | 0.01 | 0.02 | PASS |
| BJFB38 | 7.70E+03 | 7.49E+03 | 7.78E+03 | 7.66E+03 | PASS | 0.01 | 0.02 | PASS |
| FLXD50 | 1.67E+06 | 1.71E+06 | 1.70E+06 | 1.69E+06 | FAIL | 0.07 | 0.07 | PASS |
| BJFY74 | 3.99E+04 | 4.20E+04 | 4.26E+04 | 4.15E+04 | PASS | 0.01 | 0.02 | PASS |
| BJFH22 | 4.75E+05 | 5.01E+05 | 5.04E+05 | 4.93E+05 | FAIL | 0.02 | 0.03 | PASS |
| In SUBUS terminal | | | | | | | | |
| CJRL33 | 7.21E+02 | 6.71E+02 | 5.83E+02 | 1.00E+03 | PASS | N/A | N/A | N/A |
| CJRL49 | 4.00E+01 | 5.10E+01 | 6.50E+01 | 1.00E+03 | PASS | N/A | N/A | N/A |
| CJRP81 | 2.95E+03 | 2.79E+03 | 2.87E+03 | 2.87E+03 | PASS | N/A | N/A | N/A |
| CJRR35 | 9.13E+01 | 5.58E+01 | 5.08E+01 | 1.00E+03 | PASS | N/A | N/A | N/A |
| CJRR38 | 4.66E+06 | 4.72E+06 | 4.57E+06 | 4.65E+06 | FAIL | N/A | N/A | N/A |

## NPET Measurements Modes

The **Official Swiss Test Mode** is compliant with SR 941.242, in 40 s it takes and averages three separate 5 s samples. The test average is then compared to the regulation limit ($2.5x10^5$ particles cm$^{-3}$) and the instrument displays pass or fail. Alternative: General Purpose/Research Test Mode.

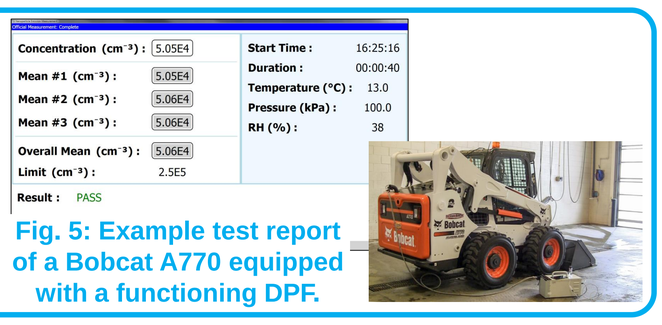


Fig. 5: Example test report of a Bobcat A770 equipped with a functioning DPF.

## Conclusion and Summary

The **Nanoparticle Emission Tester (NPET)** is well suited for in-use conformity and maintenance testing of diesel-powered, **non-road mobile machinery (NRMM)** as well as vehicle inspection and maintenance programs. It can reliably determine if the installed DPF is working properly or if it is damaged and needs to be replaced. This can be used as a quick validation of any vehicle fleet (e.g. delivery vans, taxis and buses). However, the NPET is the first instrument to receive the Swiss Federal Institute of Metrology (**METAS**) module B **type approval**, allowing instruments to be used to test according to SR 941.242.

## References


**Bischof, O.F. (2015).** Recent Developments in the Measurement of Low Particulate Emissions from Mobile Sources. *Emiss. Control Sci. Technol.* Vol. 1, (2).
**Horn, H.-G. et al. (2014).** Technical Aspects of the First Generation PN Field Instrument, 18th ETH–NPC, Zurich, Switzerland, June 25, 2014.
**Mayer, A., et al. (2004).** Reliability of DPF-Systems: Experience with 6000 Applications of the Swiss Retrofit Fleet, *SAE Technical Paper* 2004-01-0076.
**SR 941.242.** Ordinance of the FDJP on Exhaust Gas Analysers (VAMV), 19th March 2006 (latest changes effective 1st March 2014).