14th ETH-Conference on Combustion Generated Nanoparticles
August 1st – 4th 2010

Measurement of exhaust emissions of railroad locomotives using an on-board system

Michal Vojtíšek
Department of Vehicles and Engines, Technical University of Liberec
Studentská 2, 461 17 Liberec, Czech Republic, michal.vojtisek@tul.cz, tel. (+420) 774 262 854

Jonáš Jirků and Jaroslav Opava
Department of Economics and Management of Transport
Czech Technical University, Prague, Czech Republic

While the exhaust emissions of highway vehicles are being increasingly scrutinized, many old, high-emitting diesel engines are used on non-electrified railroads. On the other hand, trains are relatively fuel efficient, and locomotive diesel engines are, compared to their on-road counterparts, often conservatively rated, operate with more excess air, operate at relatively constant load with no abrupt transients, the exhaust is dispersed above the locomotive, and railroad tracks are in less immediate proximity to people than roads. This paper reports on the investigation of actual emissions of locomotives during their real-world operation, done for the purposes of comparing various modes of transport of people and goods and for the purposes of exploring the potential for locomotive emissions reduction through re-powering with newer engines, retrofits, or electrification of the tracks.

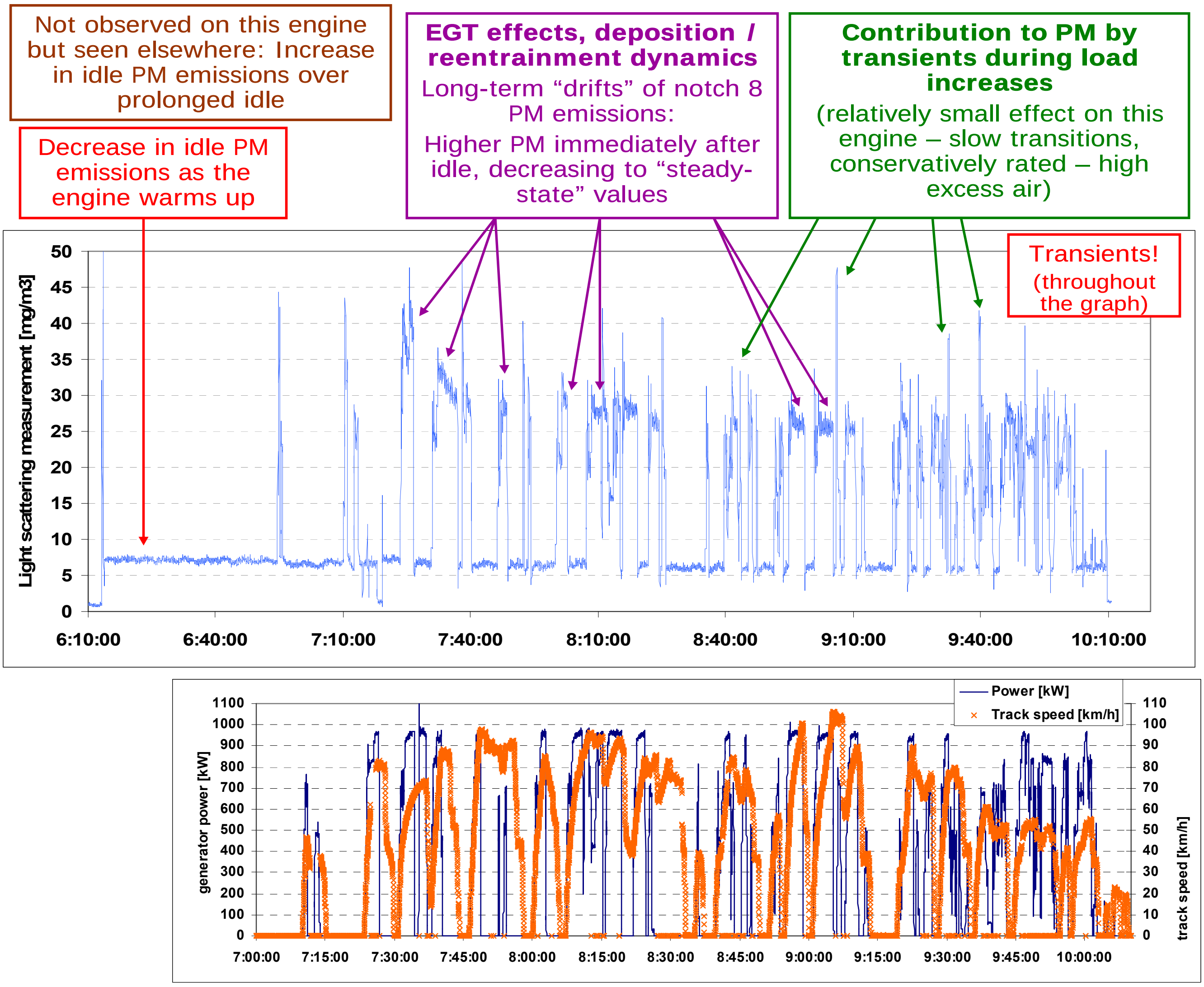
As no suitable laboratory was available for the test of a larger locomotive engine, and removal of the engine would be prohibitively expensive, alternative test methods were investigated. For diesel-electric locomotives, where diesel engine drives an electric generator, and the generated energy drives traction motors, traction motors can be disconnected and replaced by an external load bank of water-cooled resistors, which absorb the generated power, allowing the engine to be operated at load without the locomotive pulling a train. This is a relatively common approach. The engine is then operated at a series of steady-state points, starting with idle, and progressing though each “notch” (a discrete power level setting, typically, 8 notches are used) to full power. This approach has several major drawbacks. One of them was the exclusion of transients during power level changes, which are often, from visual observations on locomotives as well as measured data on road vehicles, associated with increased PM levels. Another drawback was the effect of particulate matter deposition on the exhaust system walls at idle and low loads, and its subsequent reeintrainment after progression to higher loads. Some engines, operated extensively at low loads, have built up enough particulate matter to affect high power levels for hours. Also, the traditional procedure, progressing from idle to full load in discrete steps of several to tens of minutes in lengths, is not representative of the realistic operating conditions, consisting of interleaved periods of idle and high load, with short periods of lower loads during accelerations at low speeds. Another drawback was that the load bank method could not be used on diesel-hydraulic propulsion system utilized mainly on motorized cars and motorized units.

The alternative explored within this project was to measure the emissions during the regular operation of the locomotive, avoiding the expense of removing the locomotive from the service and obtaining realistic data at the same time. Very harsh operating conditions in the engine room (heat, noise, abrupt jolts, vibrations, electromagnetic fields), presence of high-voltage electric lines directly above the exhaust stack on electrified portions of the route, limited space, tight operating schedules, and extremely high safety and reliability concerns pose unique challenges and severe constraints on the test equipment and methods which can be utilized.

In this study, a portable, on-board emissions measurement system was used to measure emissions from Czech Rail diesel locomotives on the load bank as well as during real-world operation on scheduled passenger train routes. Undiluted exhaust was sampled from a metal tube inserted into the exhaust stack at high flow rates into the monitoring system. Gaseous emissions were measured by garage-grade five-gas analyzers, dynamic concentrations of particulate matter were measured by a light-scattering instrument, calibrated by gravimetric measurements during periods of steady PM emissions at multiple operating points. Additional calibration and examination of the effects of non-standard PM sampling conditions was done at an engine laboratory on a tractor engine with similar PM emissions per unit of output. Exhaust flow was calculated from the engine operating data and design parameters. Engine power was obtained from measured values of voltage and current on the generator and assumed generator efficiency.

The results suggest that while measurement on a moving locomotive are technically very challenging, they offer a very realistic image of the actual emissions, which greatly vary depending on the operating patterns of a given locomotive. Also, on some engines, the effects of the particle deposition and reentrainment phenomena may be of such magnitude that steady PM levels are seldom reached during real-world operation.

Examples of data: Engine no. 749 107-9 with a 6-cylinder in-line 163-liter turbocharged 1500 hp diesel engine (both engine and locomotive made at ČKD, Praha, CZ, in 1968) on a scheduled passenger train run from Praha to Tanvald run with five cars. Upper graph shows PM concentrations in the exhaust, track speed and locomotive power output are shown in the lower graph.



14th ETH-Conference on Combustion Generated Nanoparticles
August 1st – 4th 2010

Measurement of exhaust emissions of railroad locomotives using an on-board system

Michal Vojtíšek
Department of Vehicles and Engines, Technical University of Liberec
Studentská 2, 461 17 Liberec, Czech Republic, michal.vojtisek@tul.cz, tel. (+420) 774 262 854

Jonáš Jirků and Jaroslav Opava
Department of Economics and Management of Transport
Czech Technical University, Prague, Czech Republic

While the exhaust emissions of highway vehicles are being increasingly scrutinized, many old, high-emitting diesel engines are used on non-electrified railroads. On the other hand, trains are relatively fuel efficient, and locomotive diesel engines are, compared to their on-road counterparts, often conservatively rated, operate with more excess air, operate at relatively constant load with no abrupt transients, the exhaust is dispersed above the locomotive, and railroad tracks are in less immediate proximity to people than roads. This paper reports on the investigation of actual emissions of locomotives during their real-world operation, done for the purposes of comparing various modes of transport of people and goods and for the purposes of exploring the potential for locomotive emissions reduction through re-powering with newer engines, retrofits, or electrification of the tracks.

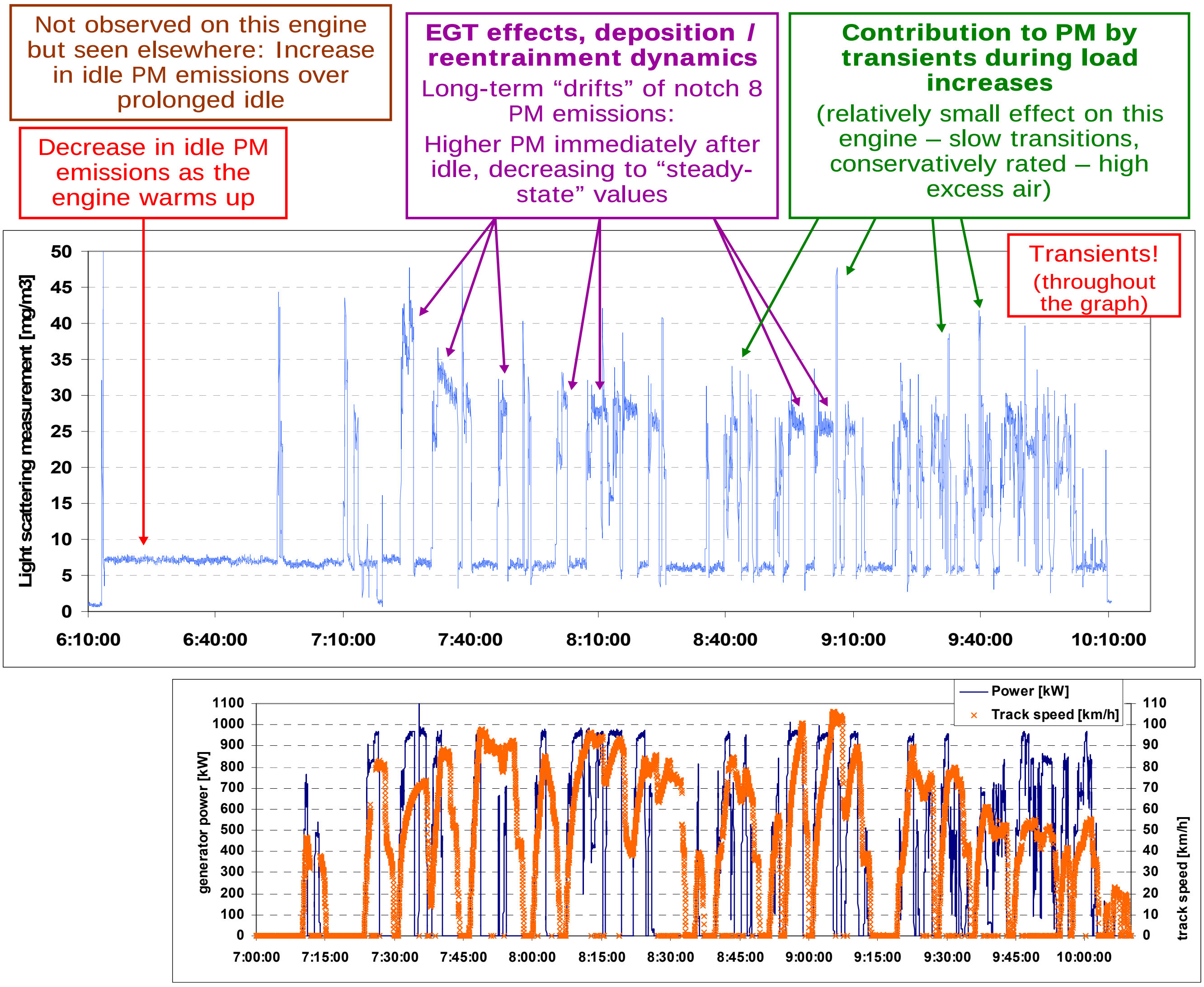
As no suitable laboratory was available for the test of a larger locomotive engine, and removal of the engine would be prohibitively expensive, alternative test methods were investigated. For diesel-electric locomotives, where diesel engine drives an electric generator, and the generated energy drives traction motors, traction motors can be disconnected and replaced by an external load bank of water-cooled resistors, which absorb the generated power, allowing the engine to be operated at load without the locomotive pulling a train. This is a relatively common approach. The engine is then operated at a series of steady-state points, starting with idle, and progressing though each “notch” (a discrete power level setting, typically, 8 notches are used) to full power. This approach has several major drawbacks. One of them was the exclusion of transients during power level changes, which are often, from visual observations on locomotives as well as measured data on road vehicles, associated with increased PM levels. Another drawback was the effect of particulate matter deposition on the exhaust system walls at idle and low loads, and its subsequent reeintrainment after progression to higher loads. Some engines, operated extensively at low loads, have built up enough particulate matter to affect high power levels for hours. Also, the traditional procedure, progressing from idle to full load in discrete steps of several to tens of minutes in lengths, is not representative of the realistic operating conditions, consisting of interleaved periods of idle and high load, with short periods of lower loads during accelerations at low speeds. Another drawback was that the load bank method could not be used on diesel-hydraulic propulsion system utilized mainly on motorized cars and motorized units.

The alternative explored within this project was to measure the emissions during the regular operation of the locomotive, avoiding the expense of removing the locomotive from the service and obtaining realistic data at the same time. Very harsh operating conditions in the engine room (heat, noise, abrupt jolts, vibrations, electromagnetic fields), presence of high-voltage electric lines directly above the exhaust stack on electrified portions of the route, limited space, tight operating schedules, and extremely high safety and reliability concerns pose unique challenges and severe constraints on the test equipment and methods which can be utilized.

In this study, a portable, on-board emissions measurement system was used to measure emissions from Czech Rail diesel locomotives on the load bank as well as during real-world operation on scheduled passenger train routes. Undiluted exhaust was sampled from a metal tube inserted into the exhaust stack at high flow rates into the monitoring system. Gaseous emissions were measured by garage-grade five-gas analyzers, dynamic concentrations of particulate matter were measured by a light-scattering instrument, calibrated by gravimetric measurements during periods of steady PM emissions at multiple operating points. Additional calibration and examination of the effects of non-standard PM sampling conditions was done at an engine laboratory on a tractor engine with similar PM emissions per unit of output. Exhaust flow was calculated from the engine operating data and design parameters. Engine power was obtained from measured values of voltage and current on the generator and assumed generator efficiency.

The results suggest that while measurement on a moving locomotive are technically very challenging, they offer a very realistic image of the actual emissions, which greatly vary depending on the operating patterns of a given locomotive. Also, on some engines, the effects of the particle deposition and reentrainment phenomena may be of such magnitude that steady PM levels are seldom reached during real-world operation.

Examples of data: Engine no. 749 107-9 with a 6-cylinder in-line 163-liter turbocharged 1500 hp diesel engine (both engine and locomotive made at ČKD, Praha, CZ, in 1968) on a scheduled passenger train run from Praha to Tanvald run with five cars. Upper graph shows PM concentrations in the exhaust, track speed and locomotive power output are shown in the lower graph.



14th ETH Conference on Combustion Generated Nanoparticles, Zurich, CH, August 1-4, 2010

Measurement of exhaust emissions of railroad locomotives during real-world operation using an on-board system

Michal Vojtíšek-Lom
Department of Vehicles and Engines
Technical University of Liberec, CZ
michal.vojtisek@tul.cz

Jonáš Jirků and Jaroslav Opava
Department of Economics and Management of Transport
Czech Technical University in Prague, CZ

Diesel powered rail vehicles
- locomotives, motorized cars, motorized units

Popular on mostly regional rail where electric traction was not implemented or is not cost-effective

Motorized cars and units

– typically use diesel engines similar to those in heavy road vehicles

- electric or hydrodynamic (automatic transmission) coupling to drive axles

- are gradually replacing locomotives

Locomotives

- used for cargo trains and larger passenger trains

- typically use large, conservatively rated diesel engines with long useful life

- mostly diesel-electric coupling (generator – electric motor)

Diesel powered rail vehicles

- locomotives, motorized cars, motorized units

- how much are they of concern in terms of emissions?

Operate in urban areas

Less strict emissions standards, older engines, slow turnaround (replacement of old engines with new ones)

Large amounts of fuel consumed

No maintenance enforcement (regular emissions inspection)

Large urban areas have mostly electric traction, diesel is limited primarily to regional trains (in Europe)

Exhaust not as close to people

Operation is far less transient

Engines are conservatively rated, no "off-cycle" emissions due to overfueling, chip-tuning, …

No low-speed transient operation in congested areas

Superior fuel efficiency compared to road vehicles

How to measure in-use emissions from diesel rail vehicles?

Traditional procedure for diesel-electric drive:

- Decouple generator from traction motors, connect the output to a **load bank** (array of water-cooled resistors to dissipate the electric energy)
- Use **transportable emissions monitoring equipment** (for vehicle or stack testing)
- Operate the engine in a **test pattern** – multiple exist, typically they require holding the engine at each "**notch**" (power setting) for minutes, starting with idle and ending with highest power

Why this did not work for our test purposes

- Locomotives are not operated in this way of "notch progression"
- Transient emissions during power increases can be responsible for large fraction of total PM
- The approach does not work for diesel-hydraulic drive (many motorized units)
- The test does not account for "storage" of PM in the exhaust during low-load operation and its release (reentrainment) after transition to high load
    - On one locomotive in Czech Republic and one in California, more than one hour of high-load operation would have been necessary to remove PM deposited in the exhaust, emission levels were not stable and test results were severely affected.
- The operating conditions (and distribution of engine loads) vary with route, train, load, …
- Economic reasons – taking a locomotive out of service is expensive, as well as its operation

Our approach: To measure during regular scheduled runs using a portable, on-board emissions monitoring system

PM reentrainment during load bank testing

(742 series locomotive, KS 6DR230 engine, Czech Railways České Budějovice depot)

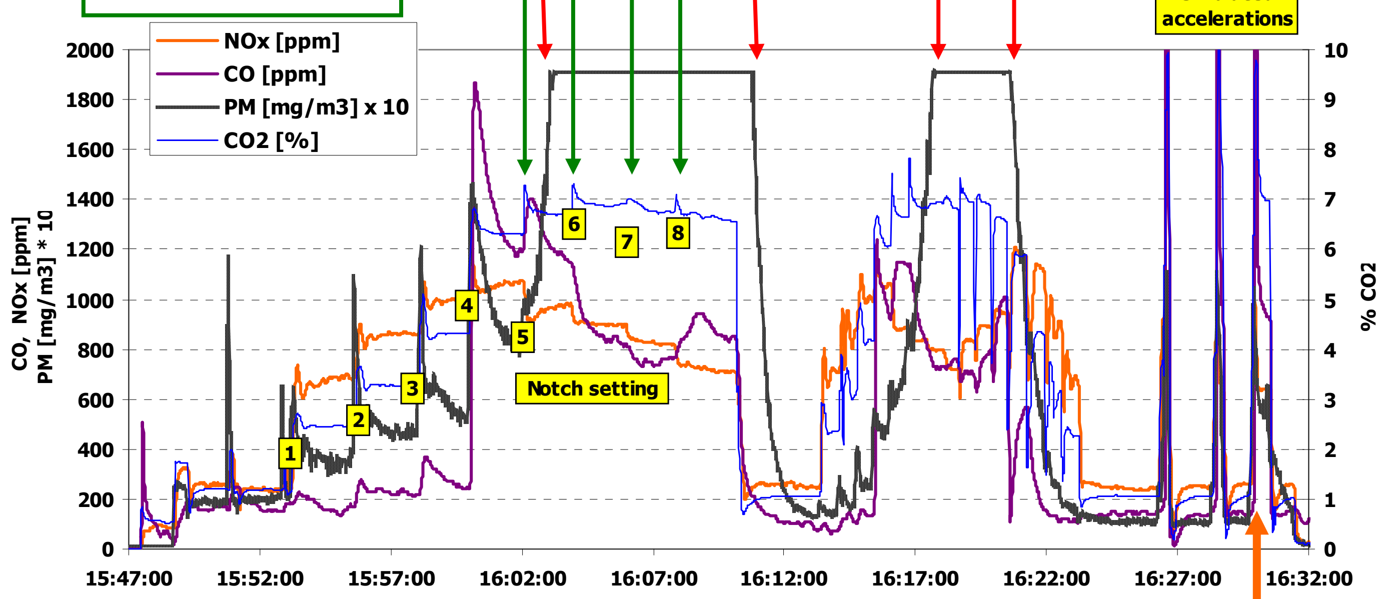
742 series locomotive used for switching (shunting) and short-haul cargo trains

Exhaust sampling

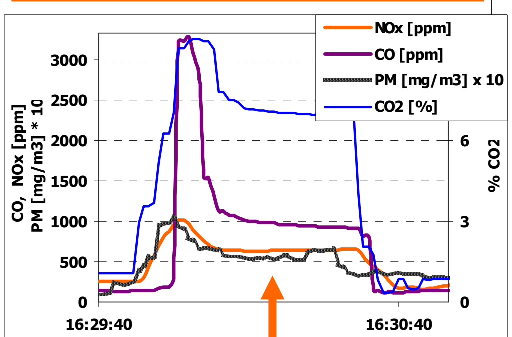
Load bank

PM overrange & visible smoke not during but after transition to high load – previously deposited particles driven from exhaust system as EGT increases

Notch transitions



PM values during short progression from idle to notch 8



749 series diesel-electric locomotive

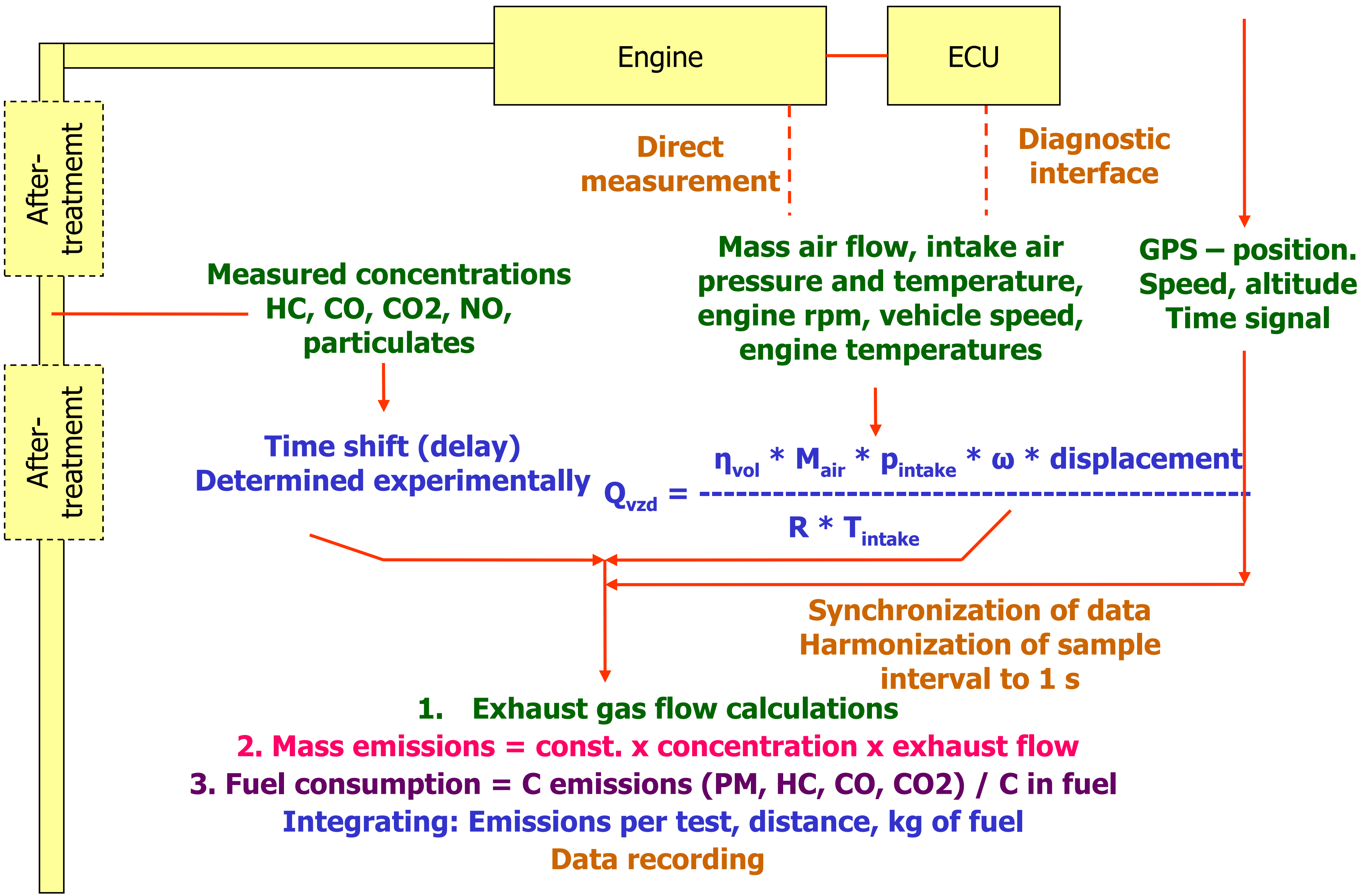
Engine no. 749 107-9, made at ČKD Praha in 1968, serial no. 7304

One of the most popular diesel locomotives in CZ

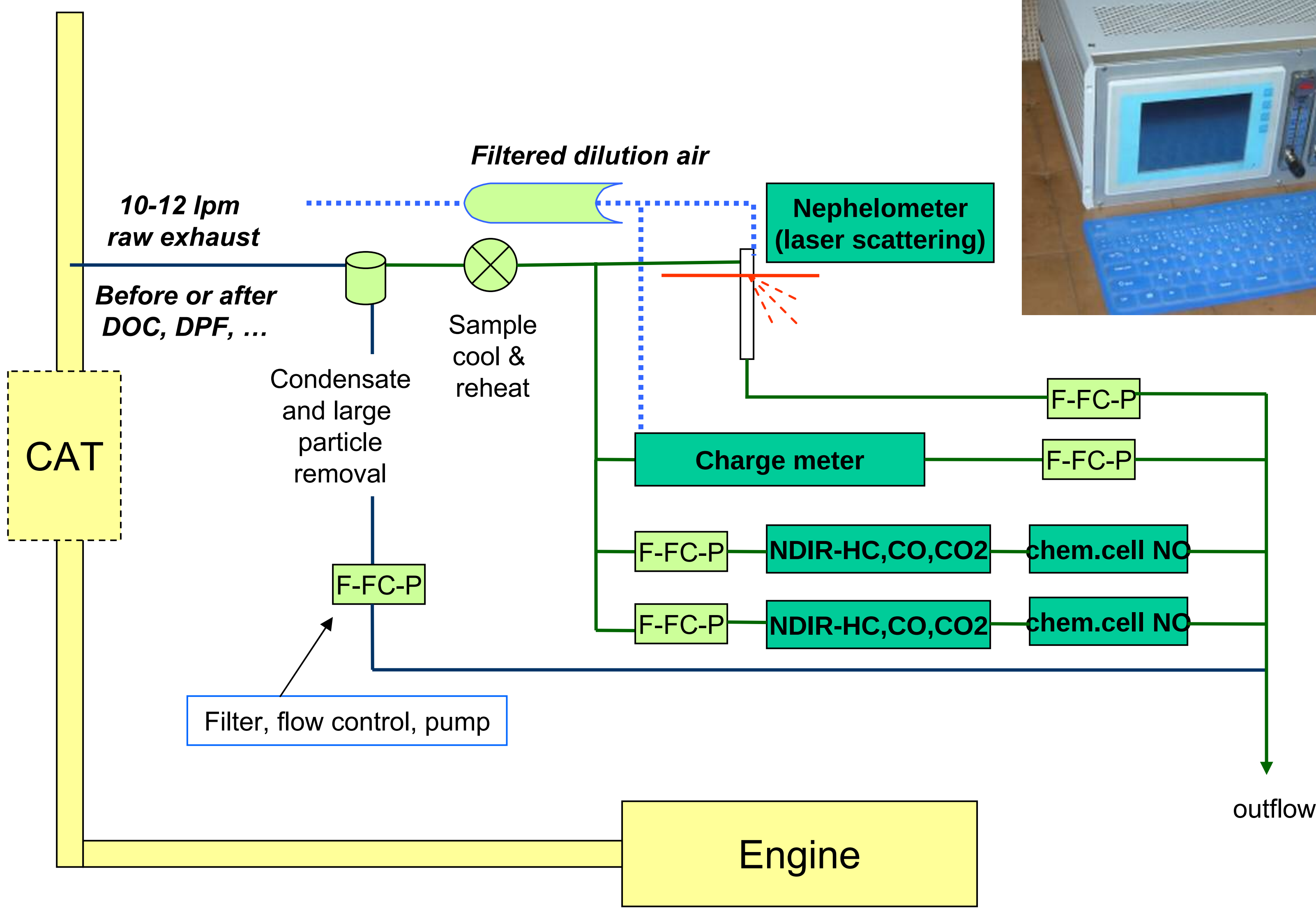
Engine: K 6S310 DR made at ČKD Praha in 1968
In-line six-cylinder direct injection turbodiesel,
four valves per cylinder, bore 310 mm, stroke 360 mm,
displacement 163.2 liters, rated power 1500 k @ 775 rpm
Power transmission: DC main traction generator
4 x DC traction motor, one per axle, max. speed 100 km/h
Accessories: Air compressor (brakes)
3000 V DC heating / accessories generator

On-board system overview

(Vojtisek-Lom and Cobb, CRC On-road vehicle emissions workshop, 1998)

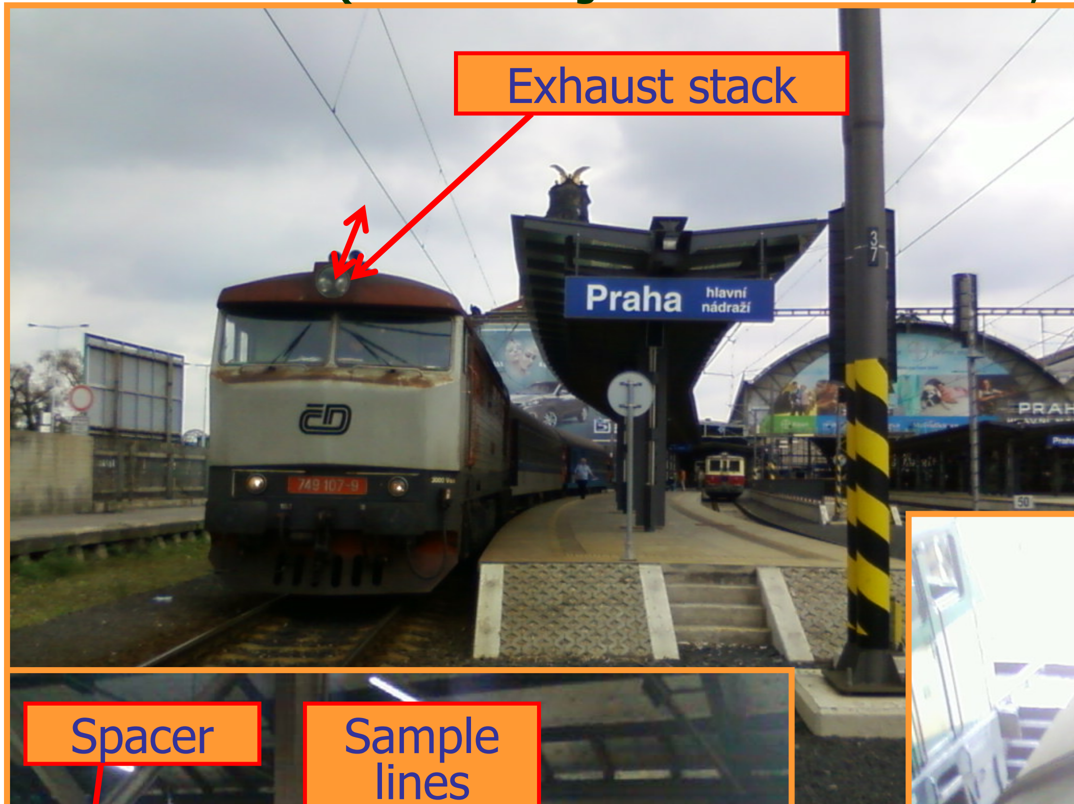


On-board system analytical hardware



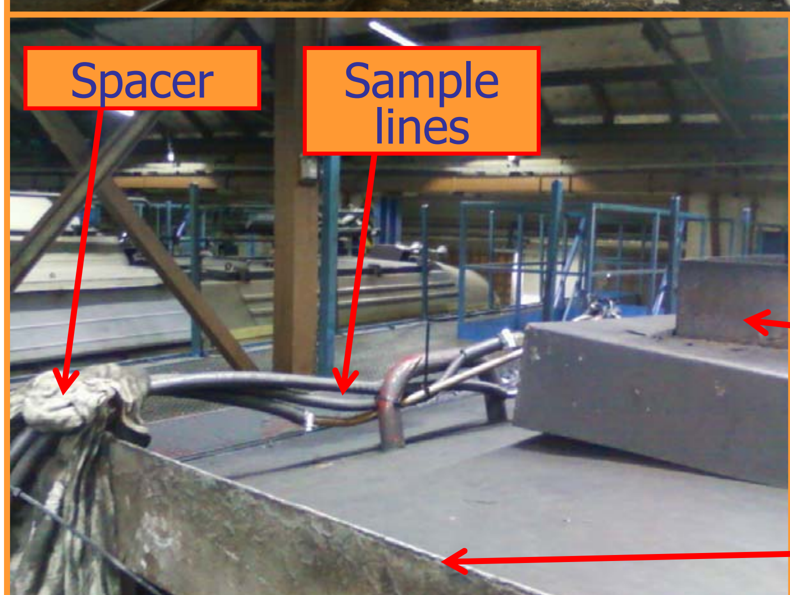
Constraint #1: Overhead traction lines (sampling)

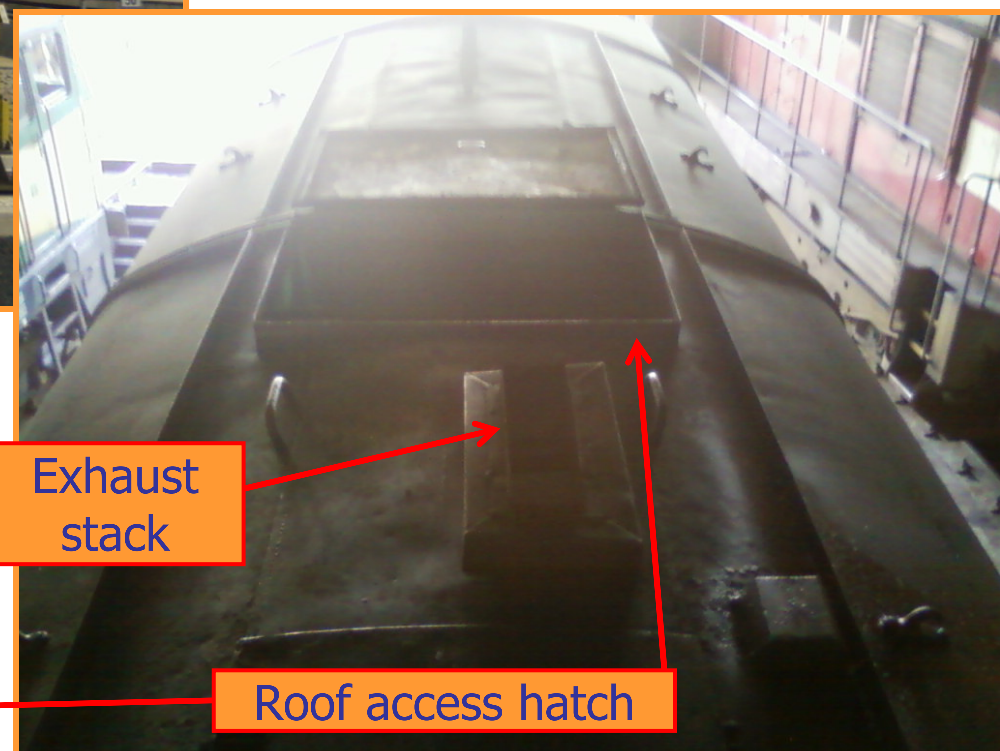
(3 kV DC Prague area and most of CZ, 25 kV AC – southern Bohemia)



Well secured, low-profile sampling system needed to ensure safe operation under overhead lines.

Probes grounded to chassis, sample lines insulated but some conductivity needed to avoid PM losses!





Constraint #2: Location of the instrumentation

☹ **Engineer cabin** - at both ends of locomotive

only one (forward) cabin is used at any time,

but the locomotive switches directions!

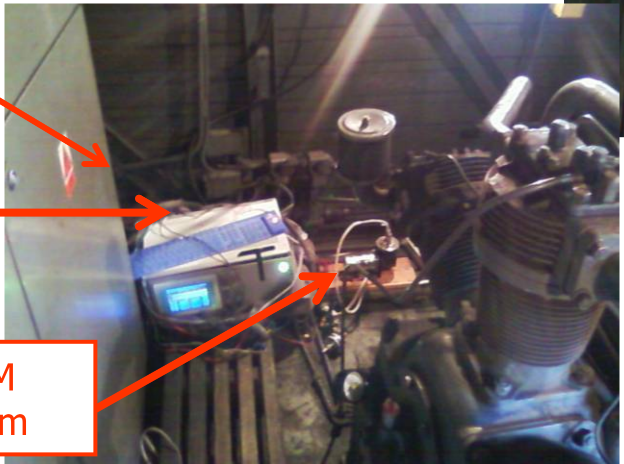
Very tight turn-around times at Prague main station (700-1000 train departures daily)

Also, no port to pass sample lines or data cables, doors must be closed, routing cables through windows not feasible – vegetation along the track

☹ **Main isle** - engineer needs to walk through the locomotive during switching (shunting)

☺ **Corner of secondary isle**

but: dark, dirty, noisy environment, next to air compressor and 3000 V DC generator



Praha – Písek – České Budějovice run

no major hills, posted limits mostly 80 and 100 km/h

Locomotive departing locomotive depo at Praha-Vršovice for 1-2 round trips

Train originates at Praha main train station (700-1000 departures daily)

Praha to Beroun run on electrified mainline rail, mostly 100 km/h

two-car express train ~160 tons

Bulk of the track is non-electrified with posted speeds varying according to the terrain profile

Praha – Tanvald run

steady climb to central bohemian plateau out of Praha
100 km/h on Praha-Nymburk mainline, mostly 80 or 100 km/h on regional rail
ascent through Jizera and Kamenice river gorges (50 km/h posted)

five-car express train, ~280 tons

Train originates at Praha Vršovice, travels through Praha main train station on high-speed mainline rail

Remainder of the run is on regional tracks served by motorized units

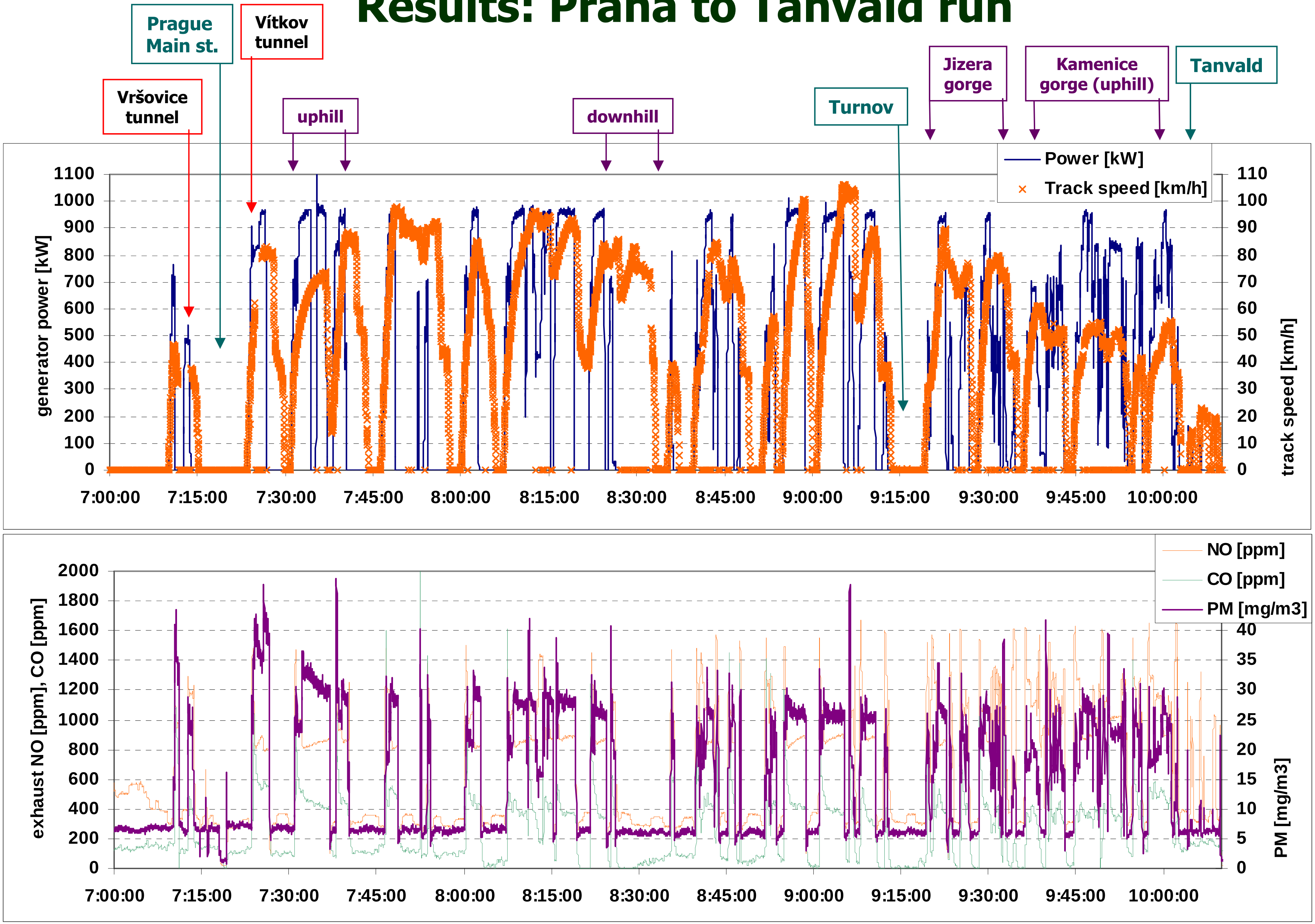
Last portion of the run is a long climb through scenic Kamenice river gorge with 50 km/h posted limit

Arriving into Praha Vysočany

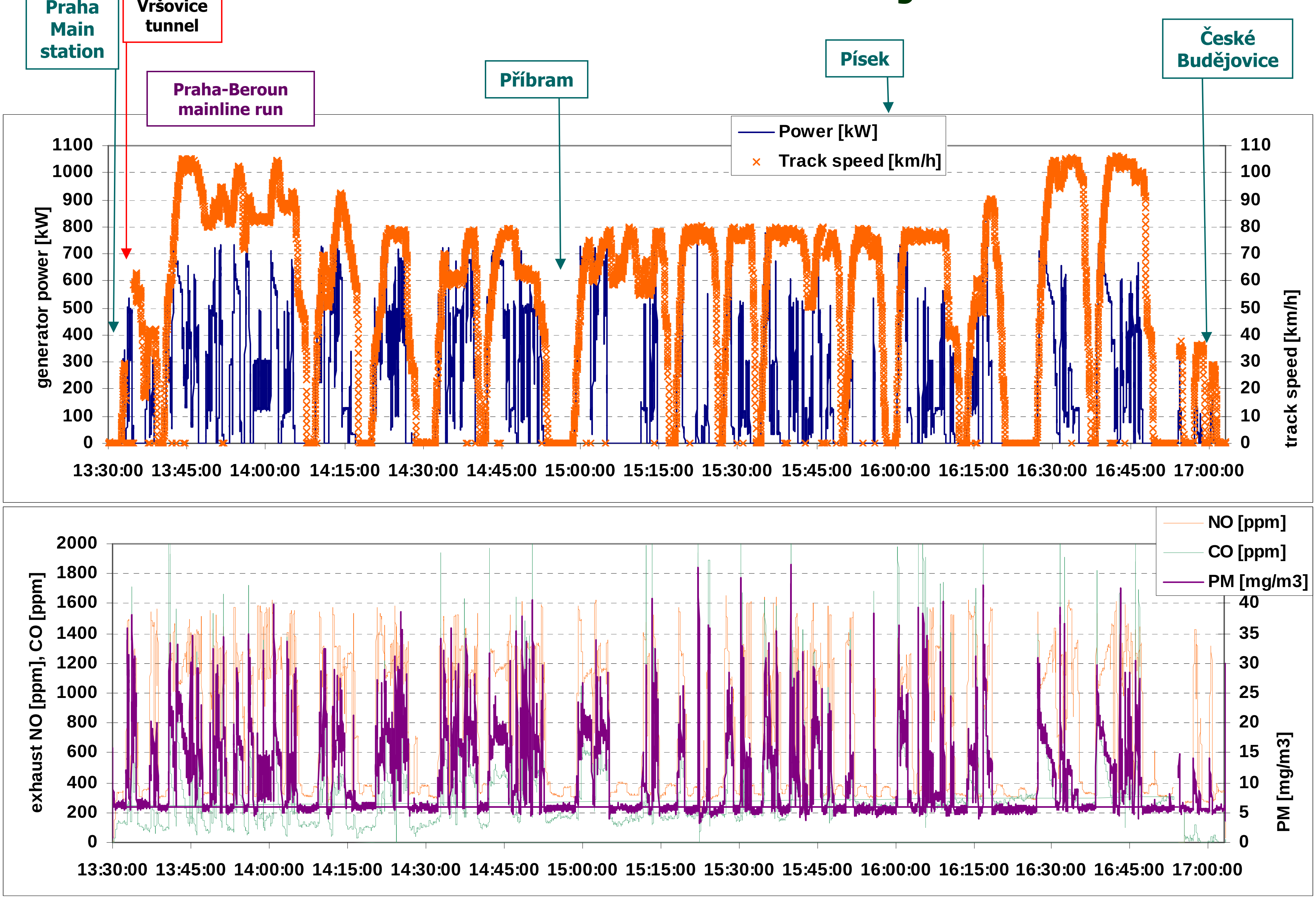
Arriving into Mladá Boleslav

Train at Tanvald station

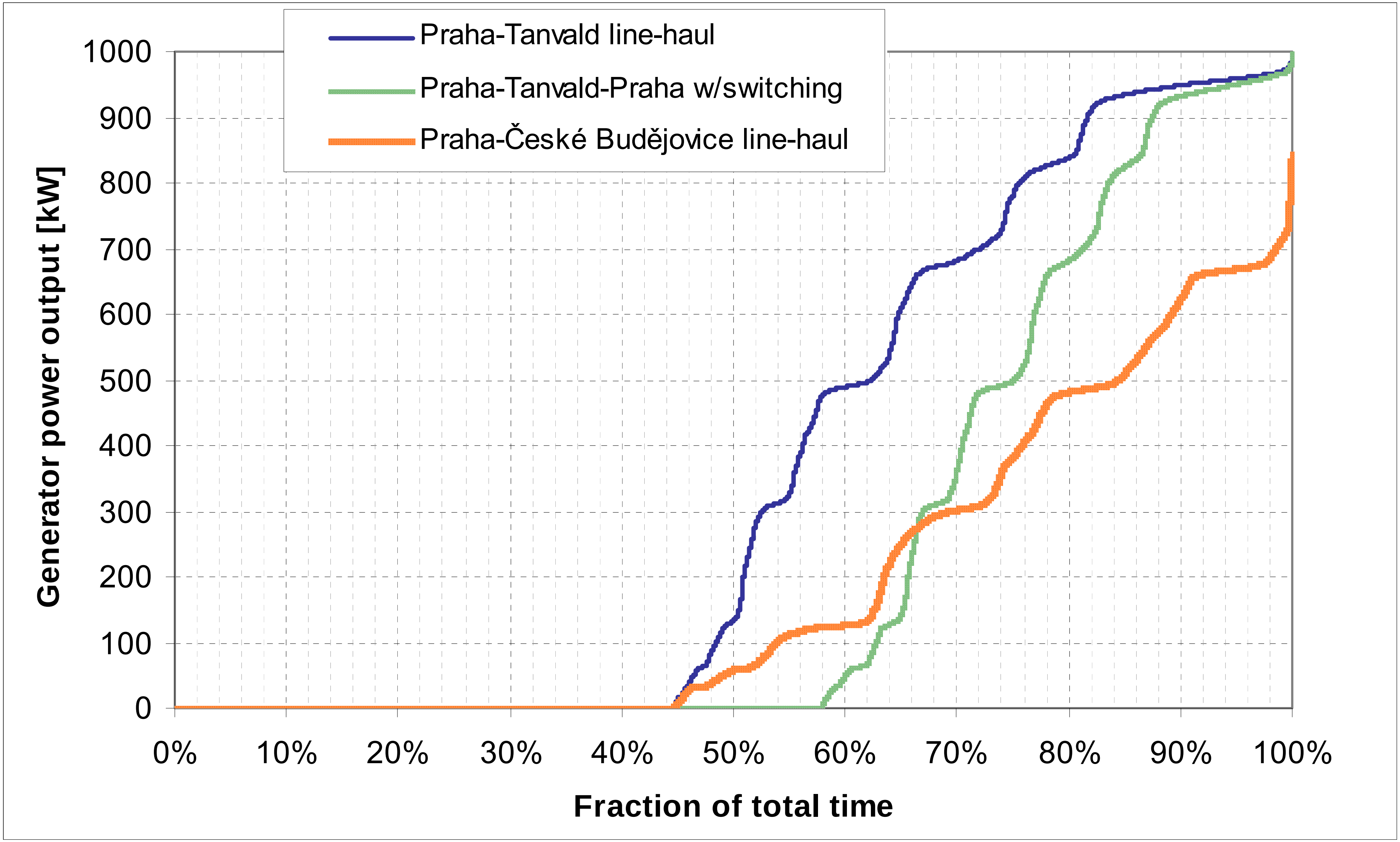
Results: Praha to Tanvald run



Results: Praha to České Budějovice run



Track load profiles

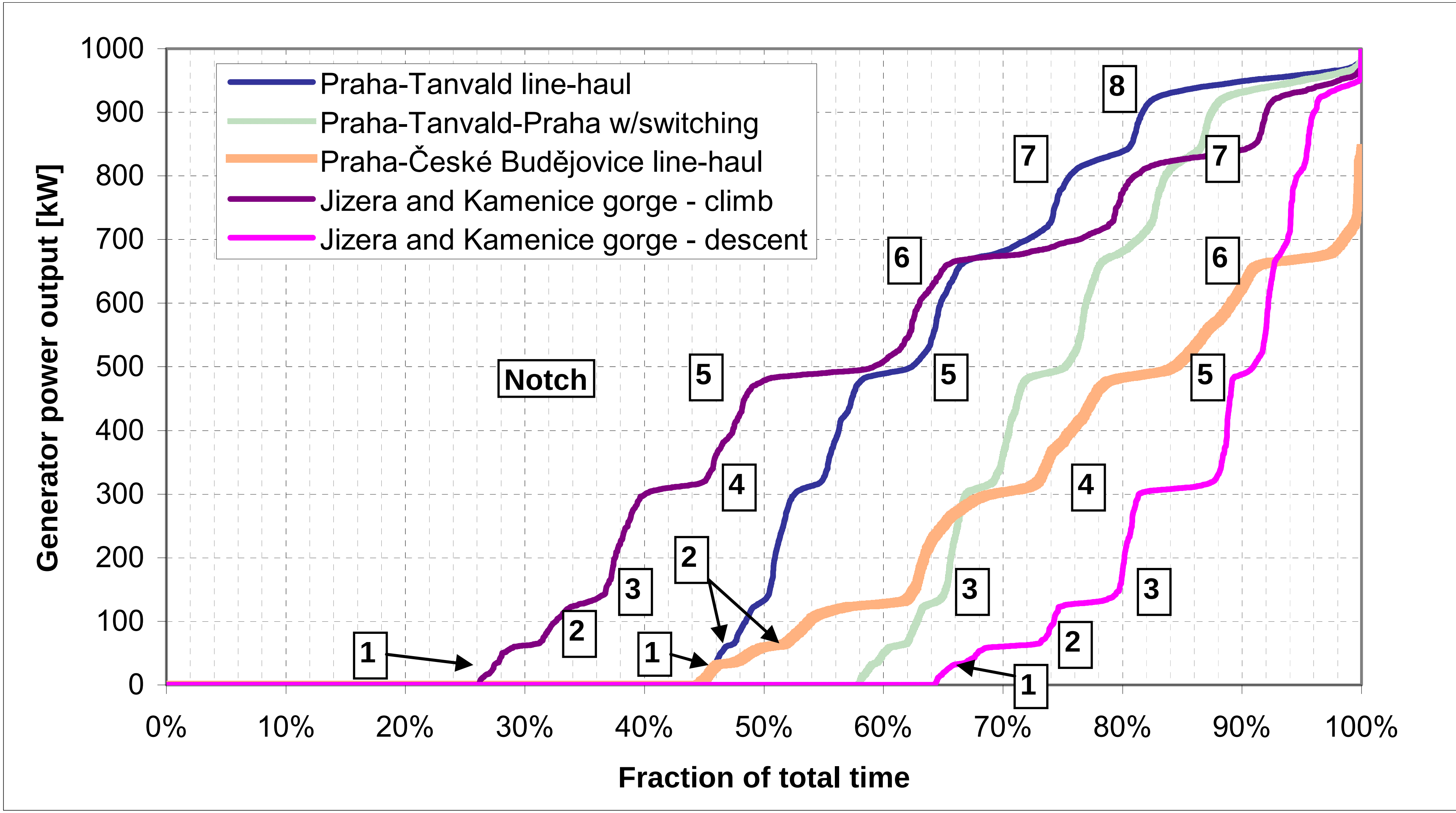


Track load profiles

"Notch" denotes a (discrete) desired power level setting of the locomotive (idle, 1, 2, … 8)

The engine fuel delivery rate, and the generator voltage, is controlled by the locomotive.

The generator voltage and speed and track speed (back-induced voltage on traction motors increases with the speed) determine the current through the traction motors. Voltage x current = power



Real-world diesel PM measurement characteristics

(this example: Praha-Tanvald run)

Not observed on this engine but seen elsewhere: Increase in idle PM emissions over prolonged idle

Decrease in idle PM emissions as the engine warms up

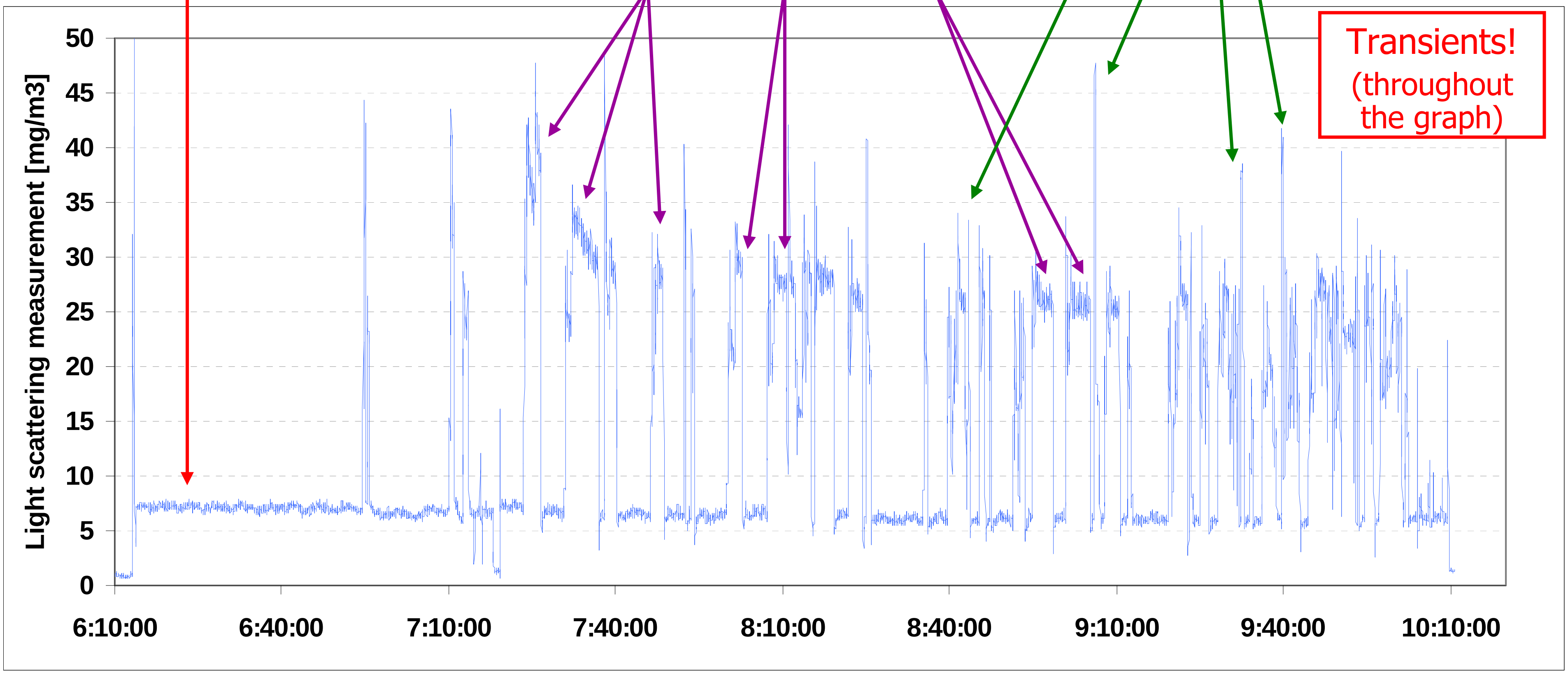
EGT effects, deposition / reentrainment dynamics

Long-term "drifts" of notch 8 PM emissions:

Higher PM immediately after idle, decreasing to "steady-state" values

Contribution to PM by transients during load increases

(relatively small effect on this engine – slow transitions, conservatively rated – high excess air)



Baseline PM measurement calibration

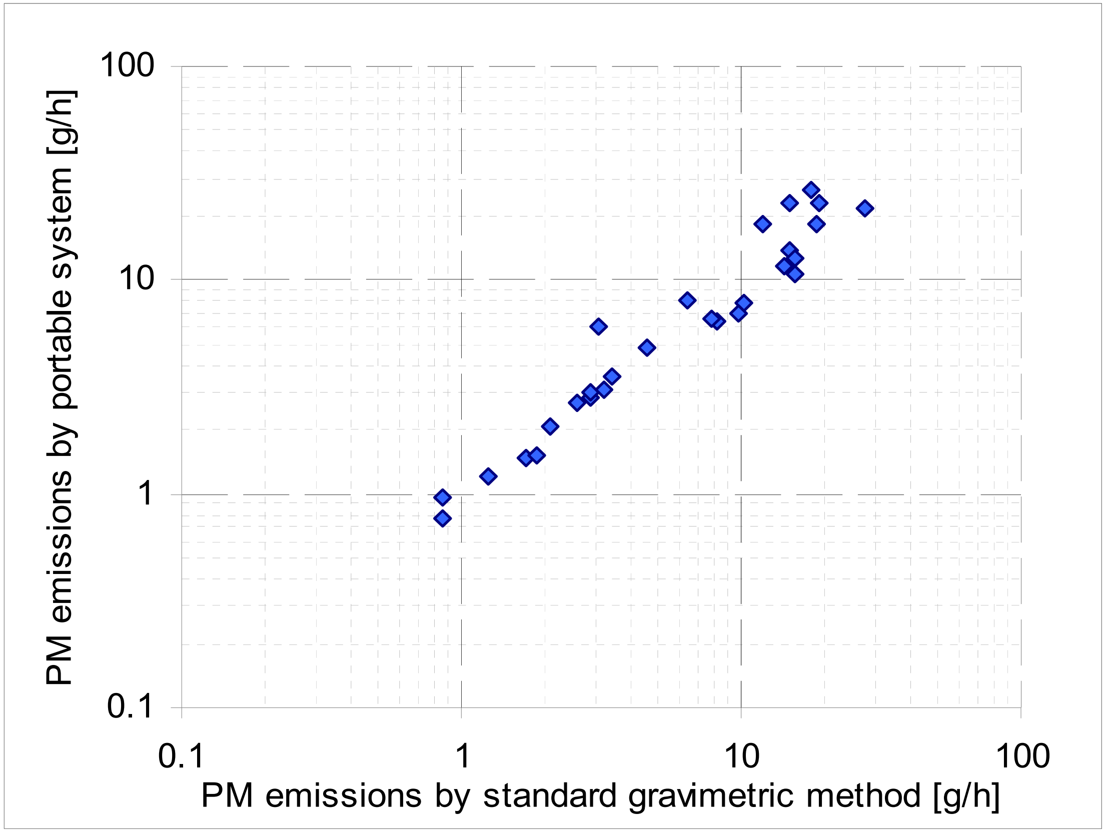
- Performed with gravimetric measurement on Zetor tractor engine (similar emissions levels as the locomotive engine) operated on diesel fuel at steady-state points
- Gravimetric samples collected on PallFlex T60A20 47-mm filters used for automotive testing – one filter per operating point
- Mass emissions rates in grams per hour calculated from both gravimetric method and on-board system results
- Portable system calibrated to match the gravimetric results over a ISO-8178 8-mode steady-state test – then calibration was verified for various operating points

Why is experimental calibration needed?

Laser light scattering response depends on particle size, composition, morphology, and other properties.

The relationships are non-linear and complex.

Not diluting or heating the sample adds to the complexity.



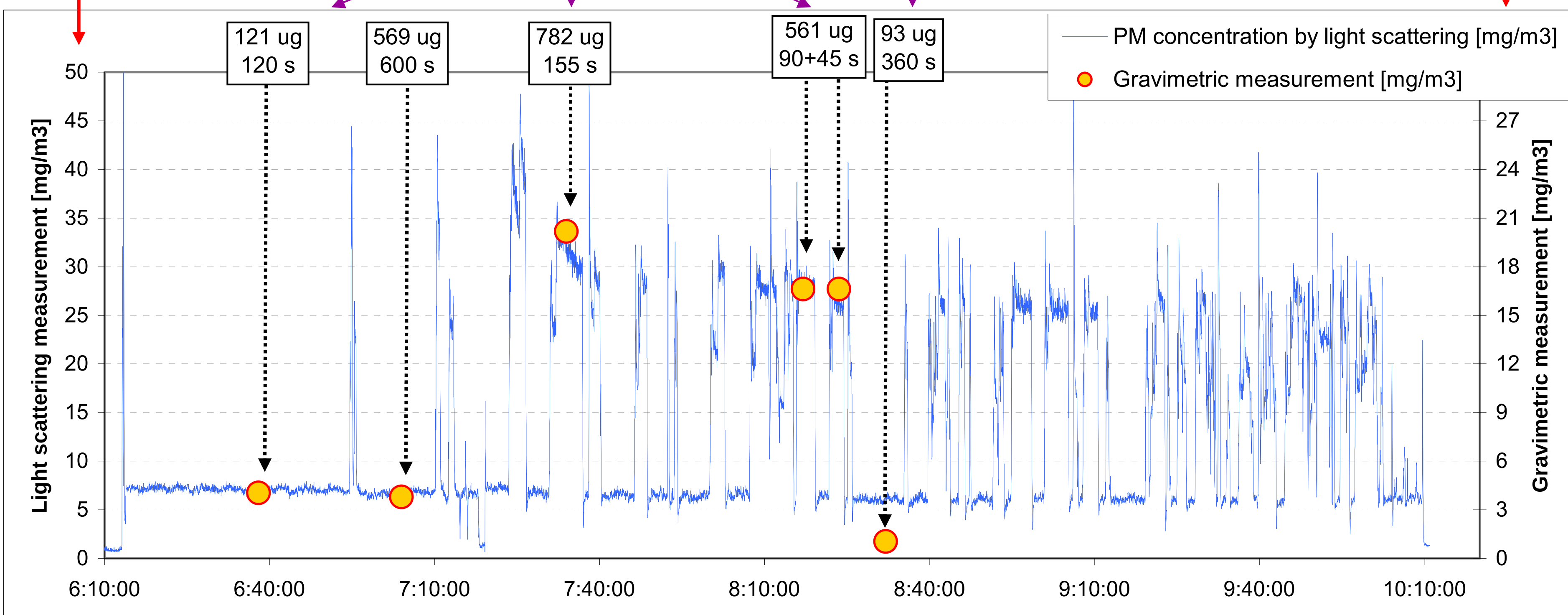
Individual PM measurement calibration

- Performed on Praha-Tanvald run during "steady-state" operation of the locomotive
- Sample collected on PallFlex T60A20 47-mm filters used for automotive testing
- Sampling rate – equivalent of approx. 15 liters per minute of undiluted exhaust
- Filters weighed at the departmental vehicle emissions testing laboratory
- Challenges: short time at a given engine load, unexpected changes in engine load, some filters damaged during handling in a moving locomotive

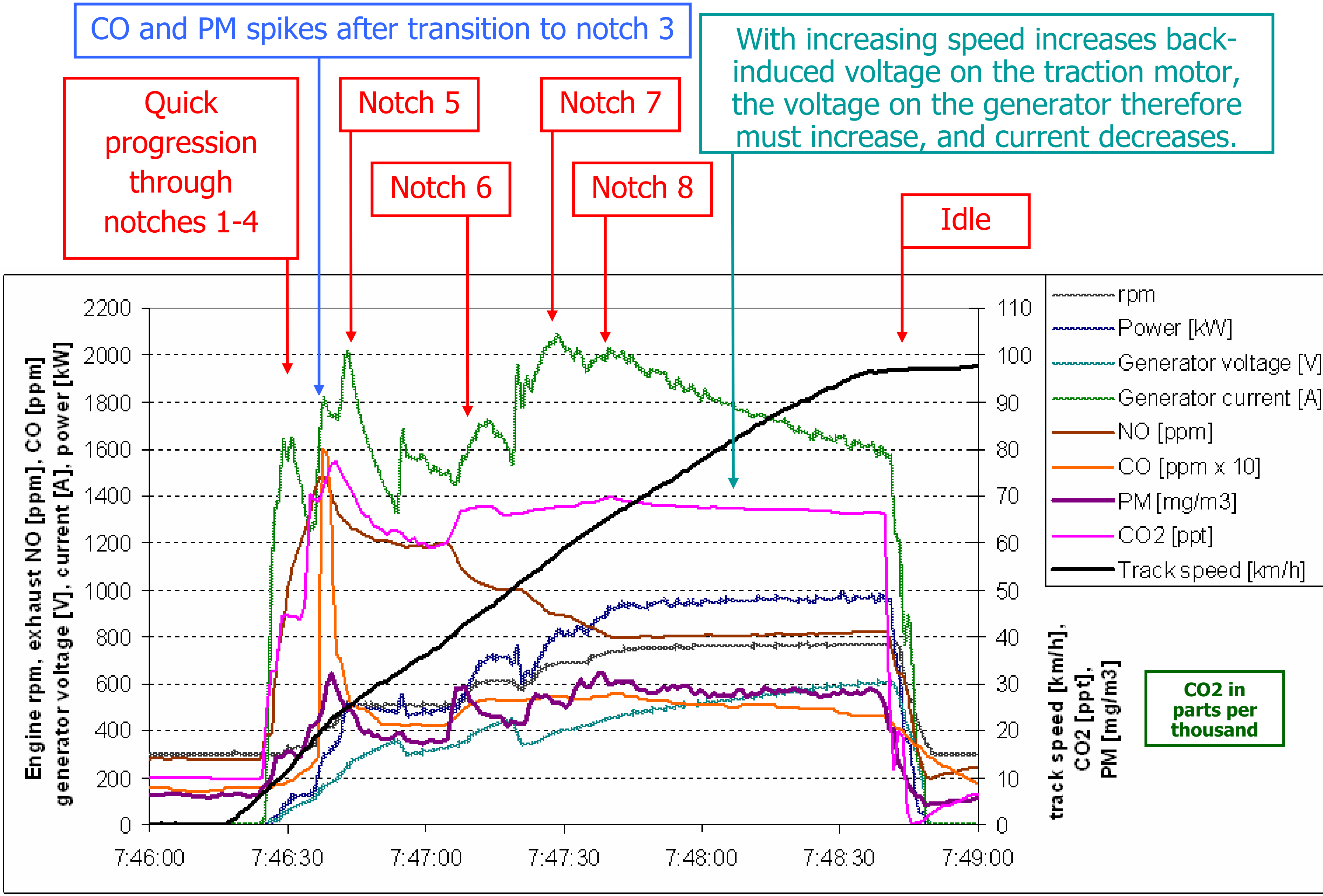
Light scattering ~ 165% of gravimetric
? Light scattering might include some organic gases (condensation) ?
? Normal deviations of the method ?

Accumulated mass, Filter sampling time

Possible filter damage



Acceleration from Praha Vysočany station



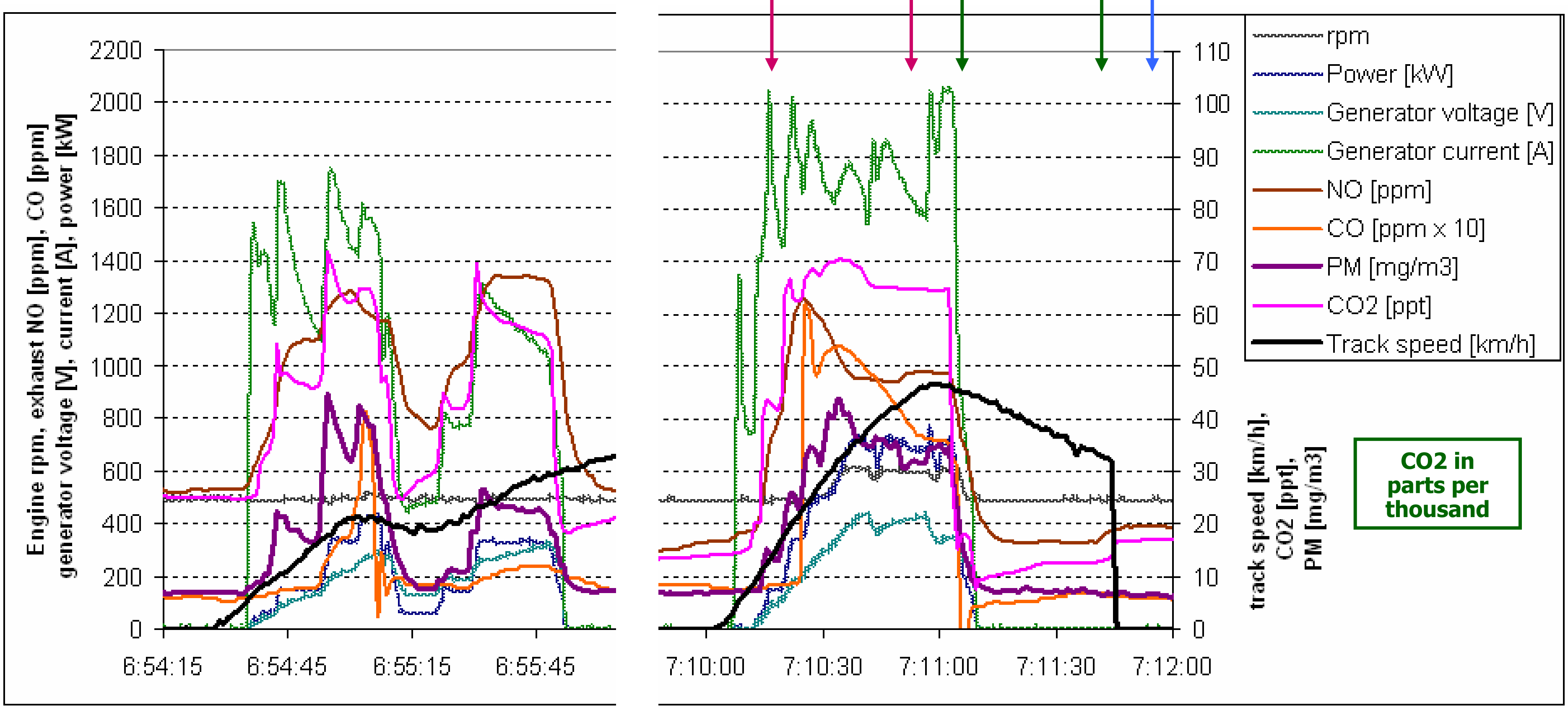
Switching (shunting) cars at Praha-Vršovice depot and station

Acceleration – very fast progression through notches, limited only by the maximum allowable traction motor current (lower speed = lower voltage = higher current) needed to get the same power

Idle / coast

Loss of GPS signal

General causes: tunnels, street canyons, river gorges, electromagnetic fields (overhead lines not a problem)



Summary results

Praha to Tanvald: 5 cars, elevation changes

Praha to České Budějovice: 2 cars, mostly flat

Trip totals	Time	Fuel [kg]	NOx [g]	CO [g]	PM [g]
Praha-Tanvald	*3:11*	*232*	*12678*	*3275*	*149*
Praha-České Budějovice	*3:21*	*152*	*11468*	*2909*	*78*

grams per kWh	Work [kWh]	Fuel [g/kWh]	NOx [g/kWh]	CO [g/kWh]	PM [g/kWh]
Praha-Tanvald	*1007*	*230*	*12.6*	*3.3*	*0.15*
Praha-České Budějovice	*659*	*231*	*17.4*	*4.4*	*0.12*

grams per km	Distance [km]	Fuel [kg/km]	NOx [g/km]	CO [g/km]	PM [g/km]
Praha-Tanvald	*136*	*1.71*	*93.2*	*24.1*	*1.1*
Praha-České Budějovice	*192*	*0.79*	*59.7*	*15.2*	*0.4*

Note: This locomotive was selected for testing by Czech Railways. It was in very good condition, with no visible smoke (except for cold start) observed throughout the run.
The emissions reported here should be interpreted as "attainable" values, and do not necessarily represent the "fleet average" which might be affected by the contribution of high emitters.

Conclusions

Exhaust emissions were measured on a Czech Railways 749 series diesel-electric locomotive used for passenger and cargo train operations on non-electrified tracks.

The measurement took place during regular scheduled runs on passenger train routes.

"On-track" NO_x, PM, CO and CO_2 emissions were measured by a portable, on-board system, placed in the engine room of the locomotive, and sampling undiluted exhaust from the stack.

Overhead electric lines and lack of space were two main challenges during on-track testing.

PM emissions were measured online by a semi-condensing integrating nephelometer, calibrated by simultaneous gravimetric measurement during steady-state operation.

The test was successful and demonstrated the feasibility of the approach chosen.

The operation of the engine was very different than during "traditional" load bank tests, and consisted of interleaved periods of idle and higher load, defined by train mass and track profile (posted speed and track grade), and relatively quick progression through lower power settings.

Transient emissions during load increases, and PM deposition at idle and reentrainment at higher load are important factors that should be considered in locomotive emissions tests.

Acknowledgements

Many thanks are given to the **Czech Railways Praha-Vršovice engine depot** for making the tests possible, to the train engineers and maintenance personnel for helpful advice and assistance with the installation of the monitoring system, and for excellent cooperation during all runs.

Authors have volunteered their time to plan for and to perform the measurement. All photos by the first author.

Travel and instrument operating expenses were sponsored by the Czech Ministry of Transport project no. CG912-058-520 ("Methodology of quantification and assessment of the environmental and safety impacts of transport").

Analysis of the data by the first author was sponsored by the Czech Ministry of Education and Youth project no. 1M6840770002 ("Josef Božek Research Centre for Engine and Vehicle Technologies II"), Action 51A201 “Experimental determination of engine emissions in the laboratory and in the real world using an on-board monitoring system”.