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Consideration of congested urban traffic in exhaust toxicity assessment

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Internal combustion engines, the prime mover of majority of road vehicles and various mobile machinery, are also major source of harmful nanoparticles in urban areas. Due to doubts whether reductions in the limits imposed on total particle mass emissions yielded a corresponding reduction in the damage to public health, and the enormous complexity of the mechanisms causing health damage, a trend has evolved of assessing the health damage potential of engine exhaust through various biological and toxicological assays. Such tests are typically carried on jointly by engine emissions and biological/toxicological laboratories.

This paper presents an argument for focusing on realistic urban operating conditions when evaluating the effects of internal combustion engine exhaust on human health.

This argument is based on the coincidence of three unfavorable factors in congested urban areas: (1) Technical challenges arising from highly variable, low average load engine operating conditions, (2) high density of engines, and (3) high density of population in the immediate vicinity of vehicle travel paths. The first argument is elaborated on in this work.

In the European Union, the emissions of light duty vehicles are measured, for type approval purposes, on NEDC driving cycle. This cycle is composed of constant speed and constant acceleration (or deceleration) segments. With most contemporary vehicles, this cycle extends from idle to moderate engine rpm and from zero to moderate load, with relatively little transients. Realistic operation in urban areas tends to be, however, more transient, and many drivers venture, often intermittently, abruptly, and for short periods, into higher loads and higher engine rpm. With increasing congestion, the fraction of time spent at idle increases and is higher compared to NEDC.

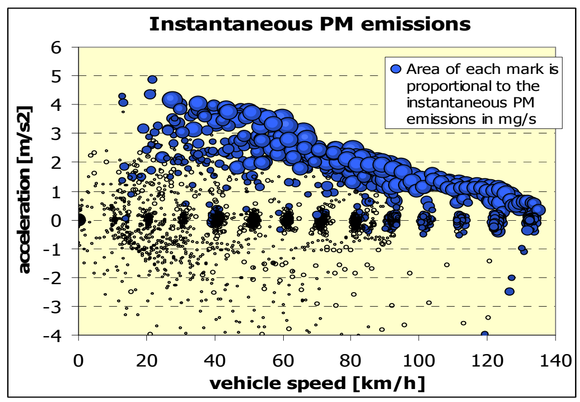

Fig. 1: PM emissions of a typical gasoline car as a function of vehicle speed and acceleration.

Traditional European automobile spark ignition engines, that is, engines featuring port fuel injection, closed-loop air-fuel ratio control using exhaust gas oxygen sensors, and three-way catalysts, produce, during relatively steady conditions at moderate speeds and loads, and when in good working conditions, very little emissions. When such engines are overfueled (operated with excess fuel relative to stoichiometric conditions), the emissions of particles (and also hydrocarbons and carbon monoxide) increase sharply. Injection of excess fuel is programmed into some engines deliberately to ensure adequate driveability during strong transients and to protect the three-way catalyst by lowering exhaust gas temperatures at high loads and at high engine rpm. As an example, the dependency of instantaneous PM emissions on vehicle speed and acceleration is plotted in Fig. 1 for a typical gasoline car (Skoda Fabia, Euro 3).

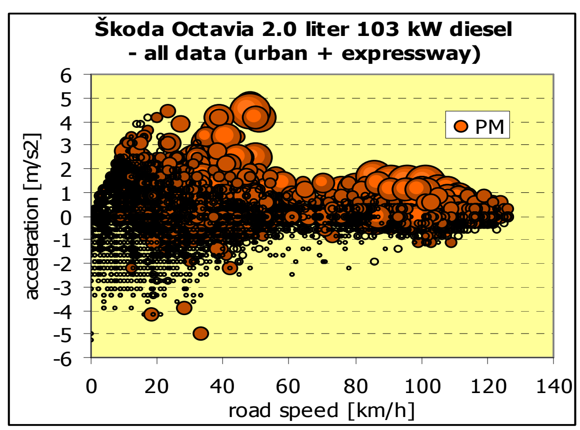

Fig. 2: PM emissions of a typical diesel car as a function of vehicle speed and acceleration.

Traditional European automobile compression ignition (diesel) engines use advanced features (such as combustion chamber geometry or high pressure multi-stage fuel injection), exhaust gas recirculation (EGR), and oxidation catalyst to maintain relatively low emission levels at moderate rpm and loads. At high loads, EGR is typically disabled to increase air flow into the engine, and the demand for additional torque is satisfied by increasing the fueling rate, until the quantity of particles, which beyond some point rises sharply, reaches some acceptable limit. On vehicles with closed-wall particle filters, the particles are retained by the filter, and the acceptable limit is given by technical concerns about the ability of the filter to regenerate. On vehicles without closed particle filters, given that full load operation is nearly always well outside of the NEDC, the “acceptable limit” is a subject to relatively open interpretation, which varies widely among manufacturers (and individuals who perform aftermarket recalibrations of engine control units to increase maximum engine torque).

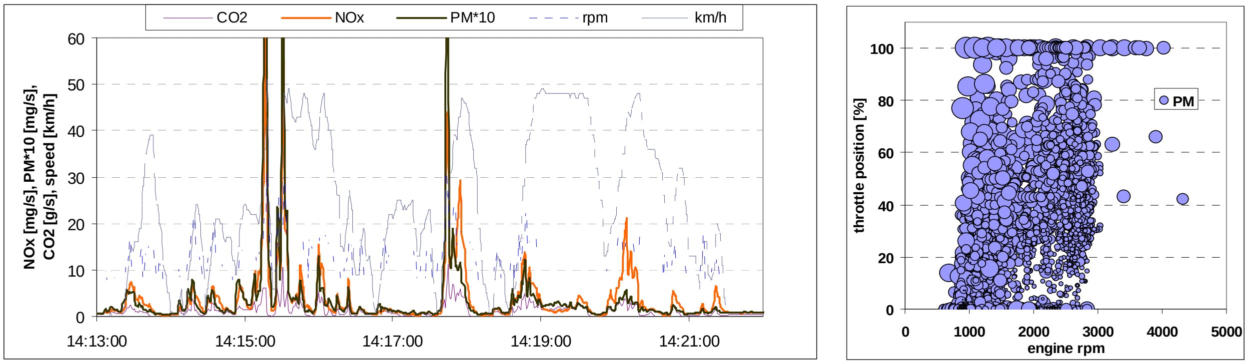

Figure 3: PM emissions from a Škoda Octavia diesel car were dominated by short spikes primarily during accelerations from low speed. Example of time traces is on the left, with "steady" driving at 50 km/h around 14:19. On the right, PM concentrations in the exhaust are plotted as a function of engine speed and throttle position (surrogate for engine load).

Utilization of turbochargers in automobile engines has increased the maximum torque at moderate and high engine speeds, resulting in smaller displacement and/or higher performance. We have observed that many accelerations out of intersections commence, however, at close to idle rpm. Given the relative scarcity of torque at low rpm, the acceleration typically occurs at high relative load. A conservatively calibrated engine limits the fueling rate, at the expense of slower takeoff. An engine calibrated for performance (“pleasure to drive“) offers an immediate response, at the expense of higher PM emissions. PM emissions from a typical Czech diesel car (Skoda Octavia) during urban driving are shown in Fig. 3 (left), where the peaks during accelerations from low speeds are visible. The concentrations of PM as a function of engine speed and throttle position (surrogate for torque) from another diesel Skoda Octavia car are given in Fig. 3 on the right.

Prolonged operation at idle or very low loads poses an emissions challenge for both automobile and heavy-duty diesel engines. The engines operate very lean, at high excess air ratios, and therefore low exhaust gas temperatures. The internal surfaces of the combustion chamber and exhaust system, including aftertreatment devices, cool down, resulting in, relative to moderate or higher loads, less complete combustion, decreased efficiency of catalytic aftertreatment devices, increased formation of secondary particulate matter within the exhaust system, and deposition of “organic carbon” (semi-volatile materials) in the exhaust system. As an example, fuel-specific NO_x and PM emissions from a Euro 5 over-the-road truck (DAF 1505 with a semi-trailer, 39 tons, Euro 5 engine with DOC and SCR) during operation on Prague perimeter road, (a freeway) are shown in Fig. 4. When travel speed (upper lline, right axis) decreases due to congestion, NO_x (middle line, red) and PM (bottom line, black) increase.

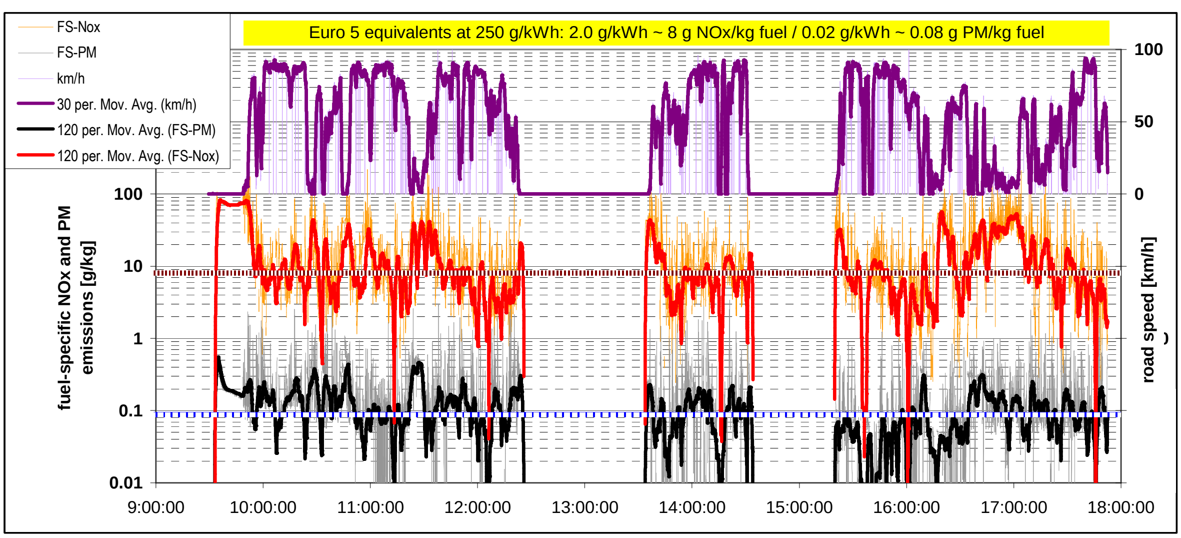

Figure 4: PM emissions from a DAF Euro 5 truck with a trailer (39 tons total weight) during operation on Prague perimeter road. NOx (middle line, red) and PM (bottom line, black) emissions per kg of fuel increase (note the logarithmic scale) when travel speed (upper line, violet, right axis) decreases due to congestion.

The problem of extended idle extends to subsequent operation, during which catalytic devices operate at reduced (or zero) efficiency until their working temperature is increased, and during which matter deposited in the exhaust system undergoes gradual removal through a combination of physical forcing, evaporation, thermal chemical transition (pyrolysis or oxidation) to gaseous form, and (not necessarily complete) combustion.

The effects of the deposits and their transformations on exhaust toxicity are yet to be fully understood, especially for emerging fuels. Removal of a puddle of fuel in an exhaust system by the flow of hot exhaust gas may be a sufficiently different process from the combustion of homogeneous mixture or finely atomized fuel to warrant such investigation. For example, non-esterified vegetable oils are known for poor combustion at idle due to their high viscosity and high boiling point (many transtition into gas phase through chemical reaction before reaching the boiling point), resulting in liquid matter deposited in the exhaust system at idle. These deposits are then driven off at higher loads in the form of white smoke with characteristic odor.

Closed particle filters seem to retain their efficiency at idle and low loads, and the extended idling problem shifts from excessive emissions to that of ensuring regeneration. However, filters can be viewed as a privilege of increasing number of countries or regions with progressive air quality policy, not a European norm, as a filter is not necessary to comply with the Euro 5 limits. For example, in Czech Republic, removal of particle filters on imported vehicles has been openly offered as a service, while in Poland, devices have been patented to emulate to the engine control unit a (removed or destroyed) particle filter.

It should be noted that the degree to which urban operating conditions affect vehicle emissions depends on the engine design and calibration, which are heavily affected by the emissions legislation applicable in the country in which the engine is sold. In the United States, excessive “off-cycle emissions” have been relatively successfully addressed by supplemental cycles (US06) for light-duty vehicles and not-to-exceed (NTE) limits for in-use emissions for heavy-duty vehicles.

It can be postulated that the question of “are we better off” (with a new emissions standard), often posed at previous ETH conferences, is likely to remain in the repertoire of the conference. Advanced engine designs tend to eliminate larger particles and elemental carbon, increasing the relative prevalence of nanoparticles and organic carbon. Both are significant from a toxicological view: nanoparticles have higher probability of deposition in the lung and can penetrate into the bloodstream, and organic carbon generally poses a higher risk than elemental carbon. The current particle number standards include only particles which are non-volatile and larger than 23 nm. Further, they are applicable only to standardized engine operating conditions. Very small, semi-volatile particles, emitted in congested city areas, are therefore likely to at least partially escape the current legislation.

The presented combination of factors suggests that a closer look at the relative toxicity of engine exhaust during typical low speed operation in congested urban areas is well warranted.

It is proposed here that the assessment of the toxicity of engine exhaust is not performed at “NEDC sweet spots” of relatively steady engine operation at intermediate rpm and load, nor at conditions representative of average operation of vehicles, but in conditions representative of realistic operation in densely populated areas, perhaps with a focus on less favorable operating conditions.

Not only such operating conditions can be viewed, in many cases, as the worst-case emissions, but also, in many cases, such conditions can be viewed as being the most representative of the exposure, with exposure measured as a combination of traffic intensity (source density) and population density (receptor density).

Measurement and sampling of exhaust during realistic urban operation, and subsequent toxicity assessments, will be the focus of the recently started European project LIFE10 ENV/CZ/651 – MEDETOX, Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic. This is a Czech national project of the Institute of Experimental Medicine of the Czech Academy of Sciences (toxicology partner, coordinator of the project), Technical University of Liberec (engine testing partner) and the Ministry of Environment of the Czech Republic (national regulatory body). This project has evolved out of a national contribution to a larger international effort to bring together engine emissions and toxicity experts and to discuss and harmonize the methodology for the assessment of the relative toxicological potential of emerging engine and aftertreatment technologies and emerging fuels.

This work was sponsored by the EU LIFE+ programme, LIFE10 ENV/CZ/651 – MEDETOX, Innovative Methods of Monitoring of Diesel Engine Exhaust Toxicity in Real Urban Traffic. Data shown here were collected by the author using a portable on-board emissions monitoring system.