Examination of PN Emissions of a Hybrid City Bus under Real World Urban Driving Conditions

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Particle emissions from city busses are especially high because of their frequent "stop-and-go" operations and corresponding transients of their diesel engines. It is well known from the literature that while a diesel engine accelerates rapidly from idling to full power, particle formation also accelerates rapidly because of turbocharger lag and combustion instabilities. In this sense hybridization of the city busses, beside many other advantages, also one of the best alternative approaches to minimize particle formation at its source. Since the secondary power source (battery or ultra-capacitor) of a hybrid city bus may provide most of the power need during rapid acceleration of the bus, the internal combustion (IC) engine may accelerate smoothly from idling to full power. Smooth acceleration of the IC engine significantly minimizes turbocharger lag and improve turbulent mixing and combustion. As a result particle formation can be minimized at its source. Therefore, hybridization of city busses may help to comply with the strict Particle Number (PN) regulations taking place over the next years.

Figure 1 and 2 compare the city bus accelerations without and with the secondary power assistance in terms of city bus traction power, engine power, and PN emissions. In these figures, speed for the first accelerations rise up to 55 km/h but the following accelerations are limited with a speed of 20 km/h for better simulation of urban driving conditions. As can be seen from Figure 1, if there is no power assistance from the secondary power source (ultra capacitor), the bus acceleration from 0 to 20 km/h speed corresponds to an engine transient from idle to maximum power and the lambda from about 5.3 to 1.6. At this condition, PN emissions sharply increase from about $1.0*10^6$ to almost $8.0*10^6$ #/cm^3. Once the engine power becomes steady at the maximum, the lambda increases to 1.9 and PN emissions reduces to as low as $1.0*10^6$ #/cm^3 again.

But, when there is power assistance from the secondary power source as shown in Figure 2, while the bus accelerates from 0 to 20 km/h speed, PN emissions remain well below that of the Figure 1. PN emission is little above $4.0*10^6$ #/cm^3 only in the acceleration that corresponds to 450th seconds. In the following accelerations PN emissions remain below $4.0*10^6$ #/cm^3. This corresponds to 50% reduction of the peak PN emissions at its source.

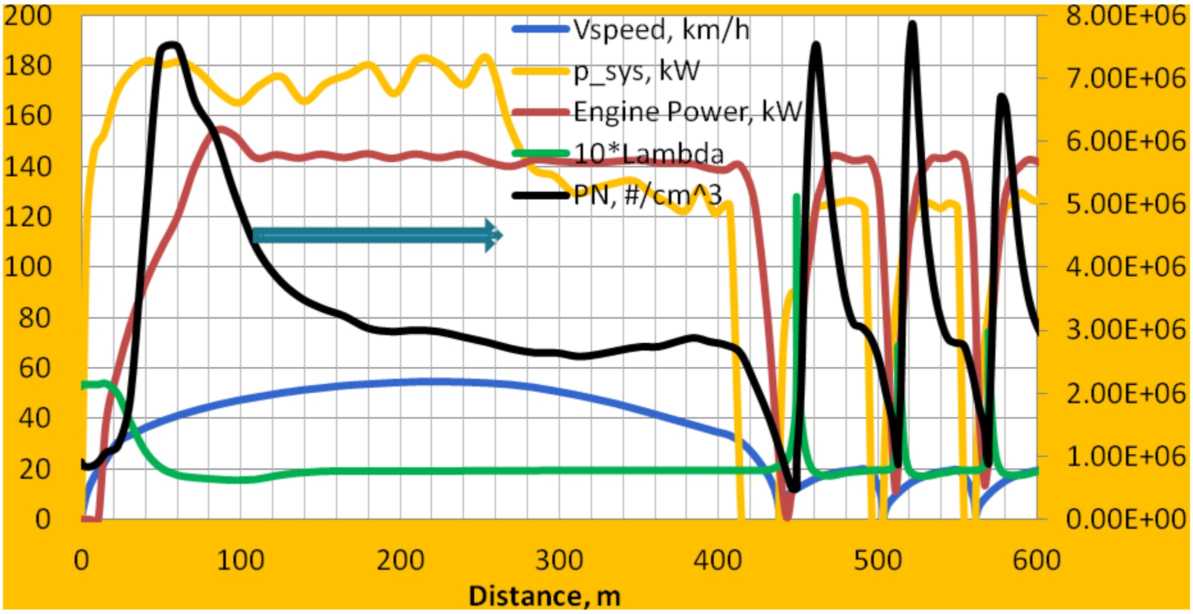

Figure 1. Effects of city bus acceleration on PN emissions without the Secondary Power Source Assistance.

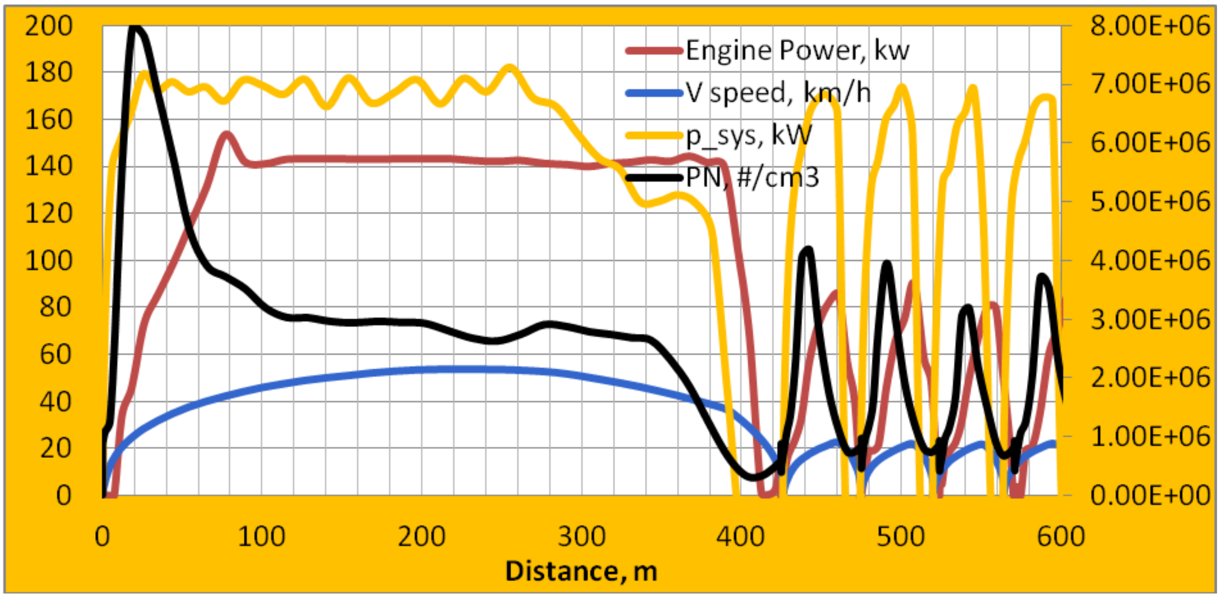

Figure 2. Effects of city bus acceleration on PN emissions with the Secondary Power Source Assistance

Acknowledgement

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2. Urs Lehmann, Martin Mohr, Thomas Schweizer, Josef R. Utter, "Number size distribution of particulate emissions of heavy-duty engines in real world test cycles", Atmospheric Environment 37 (2003) 5247–5259.

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4. Diane U. Keogh, Luis Ferreira, Lidia Morawska, "Development of a particle number and particle mass vehicle emissions inventory for an urban fleet", Environmental Modelling & Software 24 (2009) 1323–1331.

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Introduction

Particle emissions from city busses are especially high because of their frequent "stop-and-go" operations and corresponding transients of their diesel engines.

It is well known from the literature that while a diesel engine accelerates rapidly from no power to full power, particle formation also accelerates rapidly because of turbo-charger lag and combustion instabilities. In this sense hybridization of the city busses, beside many other advantages, also one of the best alternative approaches to minimize particle formation at its source.

Since the secondary power source (battery or ultra-capacitor) of a hybrid city bus may provide most of the power need during rapid acceleration of the bus, the internal combustion (IC) engine may accelerate smoothly from no power to full power.

Smooth acceleration of internal combustion engine significantly minimizes turbocharger lag and hence particle formation at its source. Therefore, hybridization of city busses may help to comply with the strict Particle Number (PN) regulations taking place over the next years.

In this work, PN emissions from a hybrid city bus were examined under real world urban driving conditions. Effects of "stop-and-go" operation of the bus on PN emissions, including size distributions, were examined in detail.

Test vehicle;

TEMSA Avenue Hybrid City Bus; 12 m long, 15 tons loaded weight

Engine: Cummins ISB6.7 Euro 5, 250 HP@2500 rpm

Hybrid system; SIEMENS ELFA with ultra-capacitors

Data sampling;

SEMTECH DS for gaseous emissions and engine operating parameters

Rotating Disc Thermodilution System from Matter Engineering

TSI 3790 for PN measurement

TSI 3090 EEPS for Particle size distribution

Results;

Figure 1 indicates speed-distance profile of "Karaman-Go" route. This is a typical route for Sakarya municipality busses. As can be seen from the figure, "stop-and-go" operations of the bus are very frequent on this route.

Figure 2 indicates a typical acceleration of the bus from zero to 70 km/h speed together with corresponding engine operating parameters and PN emissions. At this condition, while the excess air ratio (lambda) decreases immediately from approximately 5.0 to 1.7, engine speed and power start to rise up. Turbo-charger lag can be reason for such sharp decrease in lambda. During this period, turbulent engine combustion is highly instable and PN emissions rise up immediately to the maximum. Once engine speed and power become stable at the maximum, the lambda rises up to 2.0 and PN emissions decrease sharply. Diesel engines are very efficient power source to deliver high power demands of heavy duty vehicles, but it comes together with PN emissions. Engine transients from zero to higher powers are the main reason for very high PN emissions. As can be seen from the Figure, during this period while the engine delivers such a high power for this acceleration, PN emissions rise up to approximately 7.00E+6 #/cm³ of exhaust gas.

However, hybridization of city busses with a secondary power source, which can be an ultra-capacitor or a battery, can provide significant advantages in terms of reducing PN emissions at its source. Since the secondary power source may provide most of the power demands during the accelerations of the bus, engine transients from zero to higher powers can be very smooth with better mixing and combustion process.

Figure 3 and 4 indicate a comparison for the city bus accelerations without and with the secondary power assistance in terms of city bus traction power, engine power, and PN emissions. As can be seen from the figures, if there is no power assistance from the secondary power source (ultra capacitor), the bus acceleration from 0 to 20 km/h speed corresponds to an engine transient from idle to maximum power and the lambda from about 5.3 to 1.6. At this condition, PN emissions sharply increase from about $1.0*10^6$ to almost $8.0*10^6$ #/cm³. Once the engine power becomes steady at the maximum, the lambda increases to 1.9 and PN emissions reduces to as low as $2.5*10^6$ #/cm³ again.

But, when there is power assistance from the secondary power source, while the bus accelerates from 0 to 20 km/h speed, PN emissions increases from $1.0*10^6$ to only $4.0*10^6$ #/cm³. This is about 50% reduction of PN emissions at its source.

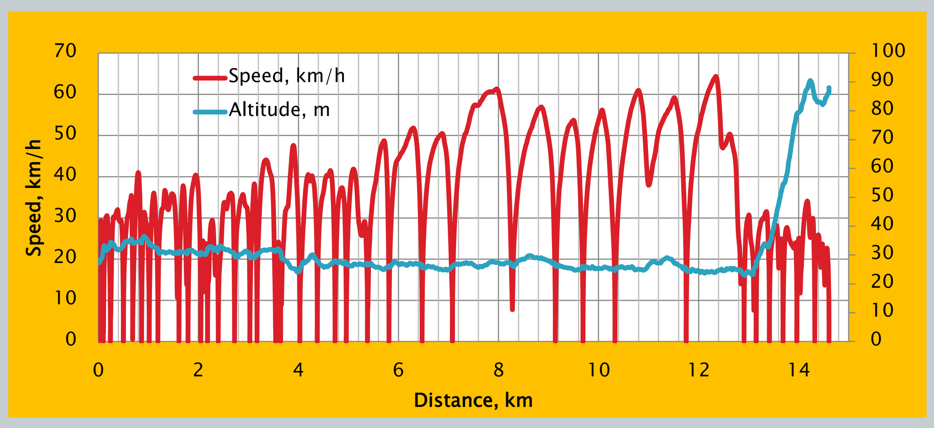

Figure 1. Speed – distance profile of Karaman route

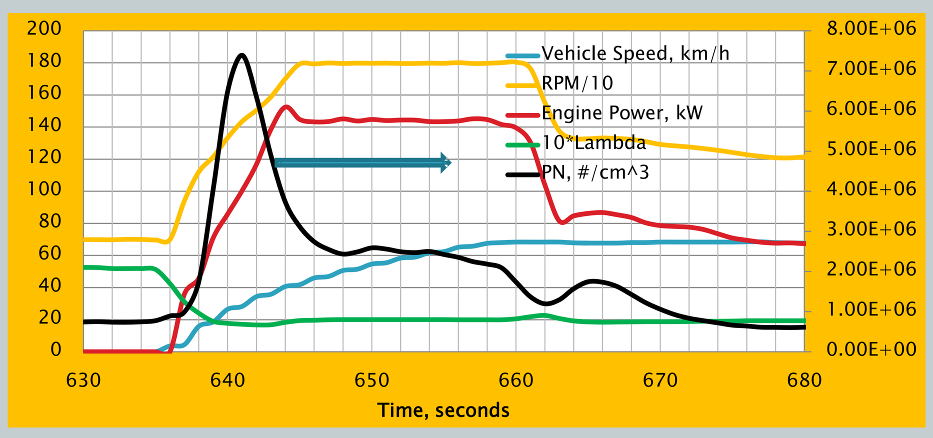

Figure 2. Effects of city bus acceleration on the engine parameters and PN emissions

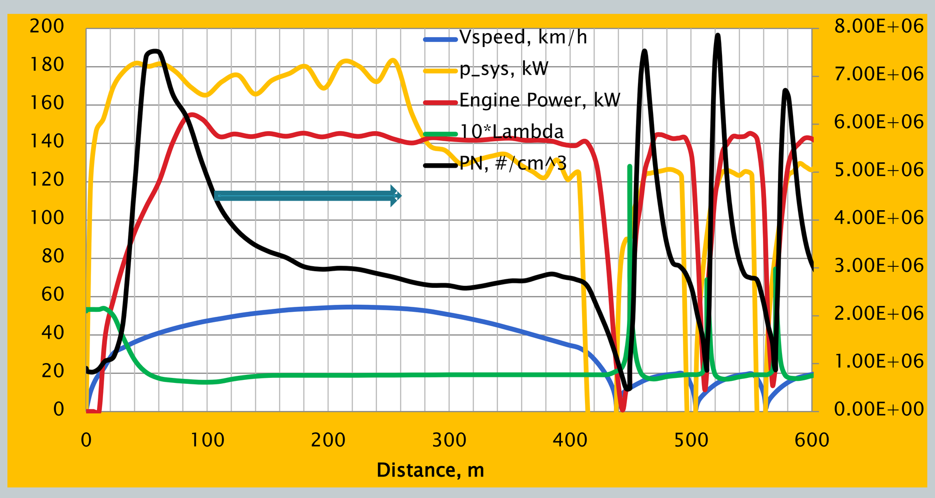

Figure 3. Effects of city bus acceleration on PN emissions without the Secondary Power Source Assistance

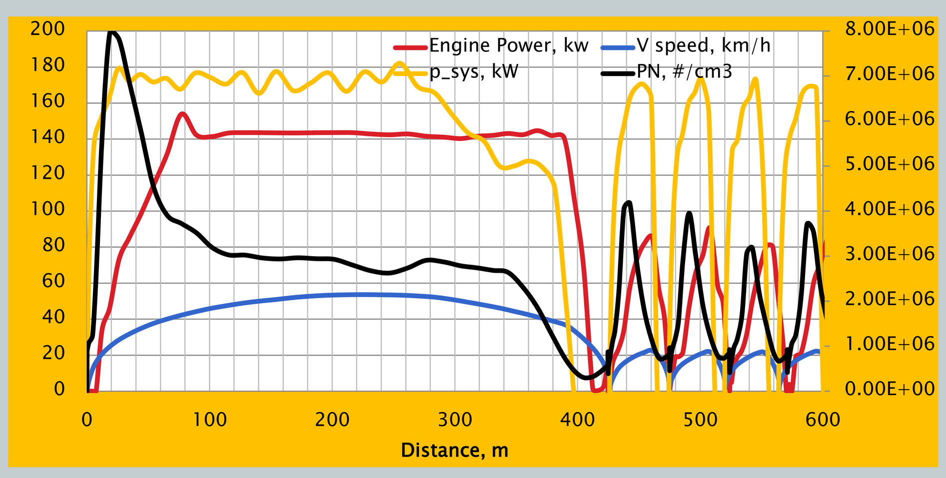

Figure 4. Effects of city bus acceleration on PN emissions with the Secondary Power Source Assistance

Figure 5 indicates particle size distributions or a period of 300 seconds. This data were collected under real-world driving conditions from "Karaman-Go" route on 25 May 2011. As can be seen from the figure, there are many peaks that correspond to the bus accelerations.

Figure 6 indicates particle size distributions for the 50th and 70th seconds for better comparison of the size distributions for acceleration and cruising conditions of the bus. As can be seen from the figure, acceleration condition size distribution have a bell shaped curve with 45 nm of mode and size range approximately from 10 to 200 nm. Under cruising conditions nucleation mode particles are dominant.

Figure 7 indicates that total PN increases with increasing engine power.

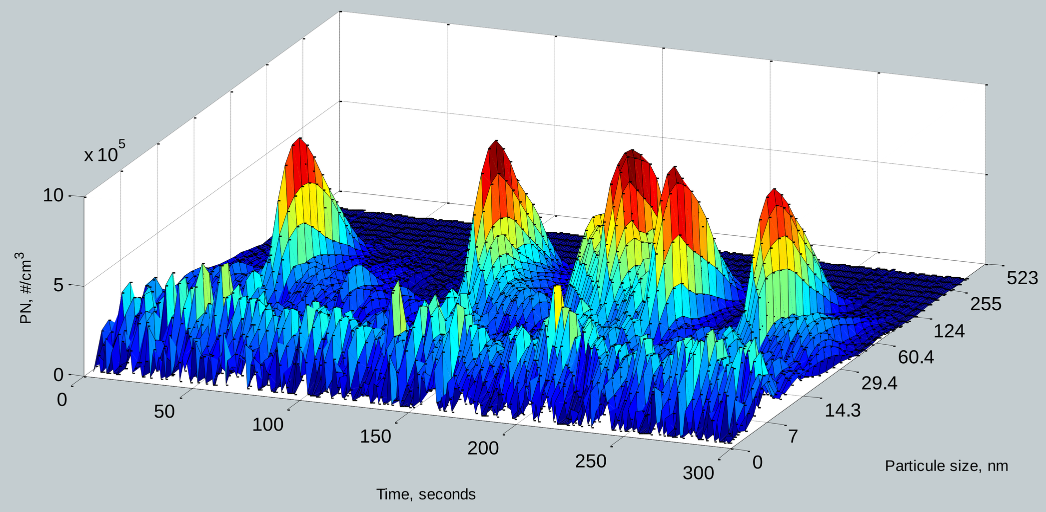

Figure 5. Particle size distribution for 300 seconds of sampling period

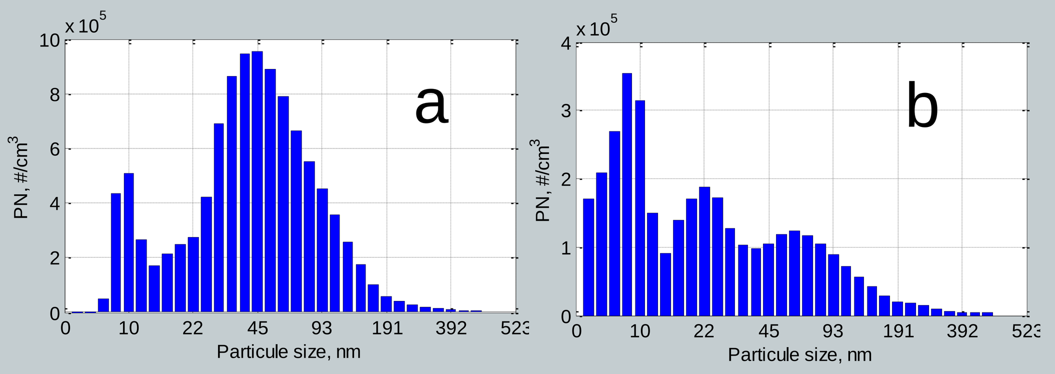

Figure 6. Effects of engine power on particle size distribution:

a) Acceleration condition size distribution (Time = 50th second)

b) Cruising condition size distribution (Time = 70th second)

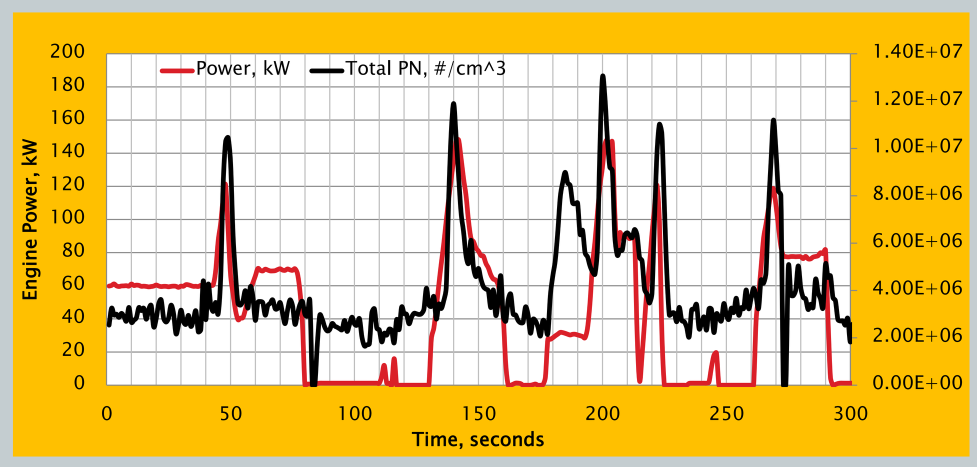

Figure 7. Effects of engine power on total particle number for 300 seconds of sampling period

Conclusions

City bus operation in urban areas requires frequent accelerations and every acceleration requires highly transient operation of the bus engine from no power to full power.

These engine transients from no power to full power are the main reason for high PN emissions due to the sharp decrease of the lambda and the combustion instabilities.

In hybrid city busses, most of the demanded power of the bus acceleration can be provided by the secondary power source and hence the engine transients can be minimized. More stable operation of the engine reduces significantly (up to 50% in this work) the PN emissions at its source.

Acknowledgment

Turkish Ministry of Science Industry and Technology and TEMSA R&D are acknowledged for their support to this project.

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