Real world PN emissions from a hybrid city bus under urban driving conditions

Seref Soylu

Sakarya University Department of Environmental Engineering 54187 Sakarya, TURKEY
e-mail: ssoylu@sakarya.edu.tr

Abstract

Particulate 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 load to full load, particulate formation also accelerates rapidly because of turbocharger lag and combustion instabilities.

Hybridization of a city bus, beside many other advantages, is one of the best alternative approaches to minimize particle formation at its source. Since the secondary power source (battery or ultra capacitor) of the hybrid city bus may provide most of the power demands of rapid accelerations of the bus, the diesel engine may accelerate smoothly from no load to full load. It is expected that smooth acceleration of a diesel engine significantly minimizes particle formation at its source. Therefore, hybridization of city busses may help to comply with the stringent Particle Number (PN) regulations taking place over the next years.

In this work, PN emissions from a hybrid city bus were measured in real time under “stop-and-go” driving conditions. The measurements were completed with a European Particle Measurement Program (PMP) compliant system. It was observed that with hybridization of the city bus, PN peak levels were reduced more than 50%. Particle size distribution measurements indicated that particles in the size range from 20 to 200 nm were very sensitive to sudden changes of engine power.

Keywords: particle number, hybrid bus, real world, emissions, stop-and-go, diesel engine

Introduction

The quantity of particle emissions released from city busses is strongly dependent on engine combustion technology, exhaust after-treatment systems, fuel quality, and city bus operating conditions. Especially for city busses, the operating conditions may have a significant effect on the quantity of particles. Depending on the traffic and road conditions, which involve many short trips with frequent accelerations and decelerations with various road grades, the quantity of the particle emissions may change by an order of magnitude (Erlandsson et al., 2008; Cocker et al., 2004; Lents et al., 2007; EC Regulation, 2009; Johnson et al., 2009; Durbin et al., 2007; Zhihua et al., 2011). It is well known that when a diesel engine accelerates rapidly from idle to higher power levels, the particle formation also accelerates rapidly because of turbocharger lag and combustion instabilities (Soylu, 2012; Kamarianakis et al., 2011).

Engine-out particle emissions can be reduced significantly by using a Diesel Particle Filter (DPF) but operating and maintenance costs of DPFs are not negligible. For this reason, it is better not to produce particles rather than reduce them with after-treatment systems. Beside, a DPF can be a source for NO_2 emissions which is also a harmful pollutant (Alverez et al., 2008).

In a technical report from the National Renewable Energy Laboratory, a conventional bus and a hybrid city bus were tested several times for fuel economy and emissions performance on four identical cycles. Each bus had a C9 type Caterpillar engine and an Engelhard DPX diesel particulate filter. According to the test report, hybridization of a city bus reduced the fuel consumption and particle emissions up to 43% and 97%, respectively (Chandler and Walkowicz, 2006). It is also well known from the author’s previous research that hybridization of a city bus can reduce real world fuel consumption up to 30%, but the amount of reduction is strongly dependent on the driving conditions (Semercioglu and Soylu, 2012; Semercioglu et al., 2010). Since a hybrid city bus also has a secondary power source, which can be an ultra-

capacitor or a battery, during sudden accelerations of the bus, most of the demanded power can be met by the secondary power source. And during sudden decelerations of the bus, most of the braking energy can be stored by the secondary power source in the form of electricity. Therefore, the diesel engine of a hybrid city bus can operate more smoothly than that of a conventional city bus and consume less fuel.

It is expected that smooth acceleration of a diesel engine reduces particle formation at its source. To prove this expectation, operating parameters and PN emissions of the hybrid city bus were measured in real time under real world driving conditions which represent frequent “stop-and-go” operations of typical city busses. The effects of real world driving conditions on the PN size distributions were examined, also. In order to better observe the effects, the operating parameters of the bus and its engine together with the PN emissions were measured second by second in real time and under real world driving conditions.

Real world driving conditions and a portable emissions measurement system (PEMS) were especially chosen rather than laboratory measurements. City bus operating conditions are quite unique for a particular city and route, hence, the well known certification test cycles cannot accurately represent these conditions. Since the test cycles do not accurately represent the real world conditions, even in the most developed countries, the quantity of vehicle emissions released in urban streets has not been reduced in parallel with their stringent emission legislations (Johnson et al., 2009; TERM, 2004; TERM, 2007; TERM, 2011; EPA Regulation, 2008). For this reason, EURO VI regulations for heavy duty vehicles require the application of PEMS for verifying real world in-use and off-cycle emissions (EC Regulation, 2009). For particle measurement, European Particle Measurement Program (PMP) compliant solid particle number and size measurement systems were chosen rather than a mass measurement system. Particle number counting (PNC) systems provide very high sensitivity to engine transients and background emissions (Andersson et al., 2010). Current regulatory mass measurement methods for determination of particle emissions have serious difficulties in accurately quantifying the low levels typically found with engines equipped with DPFs (Andersson et al., 2010).

Methodology and test setup

The test vehicle is TEMSA Avenue Hybrid City Bus. Its length is 12 m and loaded weight is 15 ton. It has a 6.7 liter Cummins diesel engine (ISB6.7) which is certified to EURO 5. It delivers 186 kW at 2500 rpm. The hybrid system of the bus is a series hybrid which is a standard SIEMENS ELFA system which has an ultra-capacitor as a secondary power source. The capacity of the ultra-capacitor is 0.725 kW-h. Hybridization of this bus was completed in the project entitled “Measurement and Modeling of Real World Emissions of a Hybrid City Bus”. This project was coordinated by Sakarya University and supported by the Turkish Ministry of Science, Industry and Technology and TEMSA R&D.

Figure 1 shows a schematic of emissions measurement system. Engine operating parameters, ambient conditions, vehicle location and tailpipe gaseous emissions measurements were made by using a SEMTECH DS from SENSORS Inc. This system collects real time data from the engine control module, the GPS module and the emissions sensors which include a flame ionization detector (FID) for total HC measurement, a non-dispersive infrared (NDIR) sensor for CO and CO2 measurement, a non-dispersive ultra violet (NDUV) sensor for NO and NO2 measurement. The exhaust mass flowrate was measured using a SEMTECH EFM which operates based on pitot tube technology. Solid particle number and size measurements system involves a rotating disc thermodilution system from Matter Engineering, a condensation particle counter (CPC 3097) and a particle sizer (EEPS 3090) both from TSI.

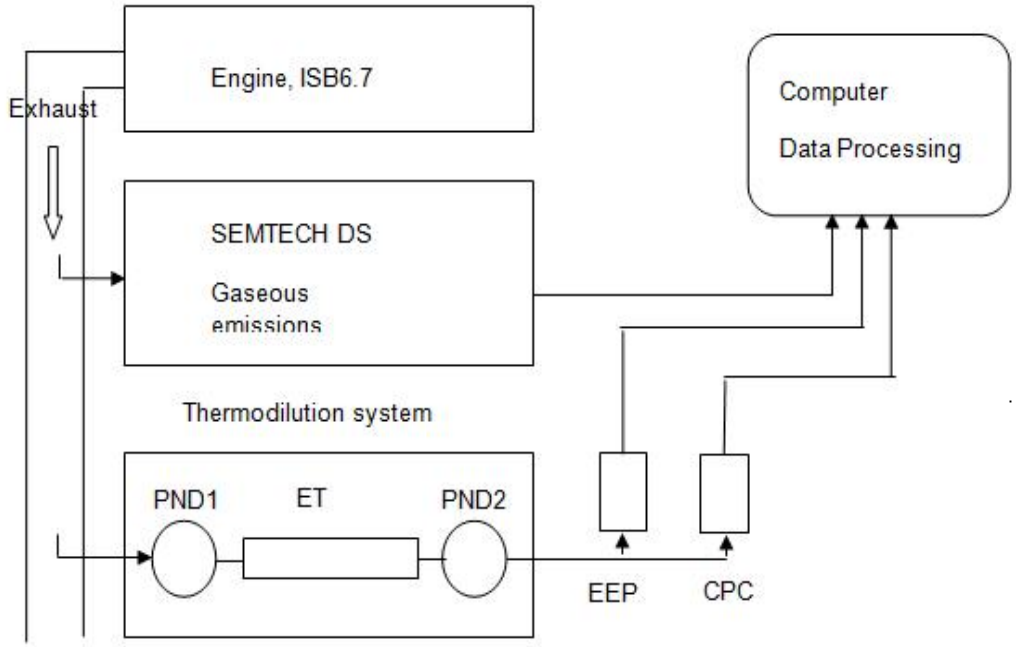

Figure 1. Schematic of emissions measurement system

Results and discussions

Since the frequent "stop-and-go" operations are common operating conditions for urban city busses, which are also the most beneficial conditions for series hybrid city busses, the tests were completed over a test cycle that involved frequent accelerations and decelerations with a maximum speed of 20 km/h. To better observe the effects of the hybridization, the bus was tested over the same route with and without power assistance from the ultra-capacitor to the bus engine. If there is power assistance from the ultra-capacitor to the diesel engine then the bus operates as a hybrid city bus. Otherwise, the bus operates more like a conventional city bus.

Figure 2a indicates the speed-distance and altitude profile over which the bus was tested without power assistance from the ultra-capacitor. In the first parts of the test, the bus accelerated up to a speed of 55 km/h and then decelerated to stop.

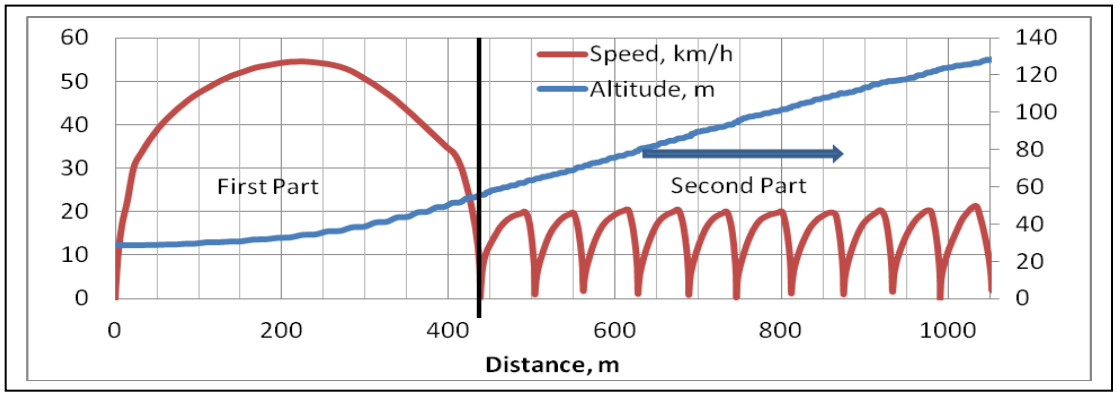

Figure 2a. Speed-distance profile of the hybrid city bus without assistance from the secondary power source.

At the end of this period, the charge level of the ultra-capacitor was minimized so that it could not provide any more assistance to the engine. In the second part, the bus was driven solely by the diesel engine as a conventional city bus. During this period, as shown in the figure, the bus driver accelerated the bus at a full load condition to the speed of 20 km/h and then decelerated to stop. These cycles were repeated 10 times in a distance of 1050 m.

Figure 2b indicates the speed-distance and altitude profile which the bus was tested with assistance from the ultra-capacitor. In order to test the bus at the same conditions, in the first part, the bus was accelerated up to 55 km/h and then stopped. During the second part, however, the test was started with a full charge level of the ultra-capacitor and the ultra-capacitor assisted the diesel engine for the accelerations of the bus. In order to reach its full charge level, the ultra-capacitor was charged both with the regenerative braking energy and the engine. Because of the assistance from the ultra-capacitor, the bus tractions power was higher and the bus speed reached to 20 km/h in the shorter distances. For this reason, the cycles were repeated 14 times for the same distance. Actually, the driver of the bus tried to accelerate the bus exactly to 20 km/h of speed for every cycle but it was not possible. As can be seen from the figure, at some of the cycles the speed was as high as 23 km/h. It was observed that such variations in the maximum speed did not make significant differences in the engine operating parameters and the emissions under real world driving conditions.

Figure 3 indicates the city bus and its engine's operating parameters during a typical acceleration of the bus from stop to 70 km/h speed together with corresponding PN emissions. This is very useful figure to understand the effects of the engine operating parameters on the 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. Turbocharger lag can be one of the reasons for such sharp decrease in lambda. During this period, turbulent engine combustion is probably 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 as can be seen from the figure during acceleration period of the engine from idling to higher powers, there is almost a direct relation between engine power and PN emissions. As can be seen from the figure, during this period while the engine is accelerating for higher powers, PN emissions rise up to approximately 7.50E+6 #/cm^3 of exhaust gas.

It is actually very important to note that while the engine is accelerating from idle to higher powers, the PN emissions immediately increase up to the maximum. Then, once the engine power becomes stable at the maximum, as shown in Figure 3, the PN emissions sharply decrease to about 30% of the maximum. There is almost a direct relation between sudden increase of engine power and PN emissions. It is probably true that during such a hard acceleration of the diesel engine, turbocharger lag and low engine speed are the reasons for insufficient turbulent mixing of the locally very rich fuel-air mixture in the cylinder and, hence, the very high number of particle emissions.

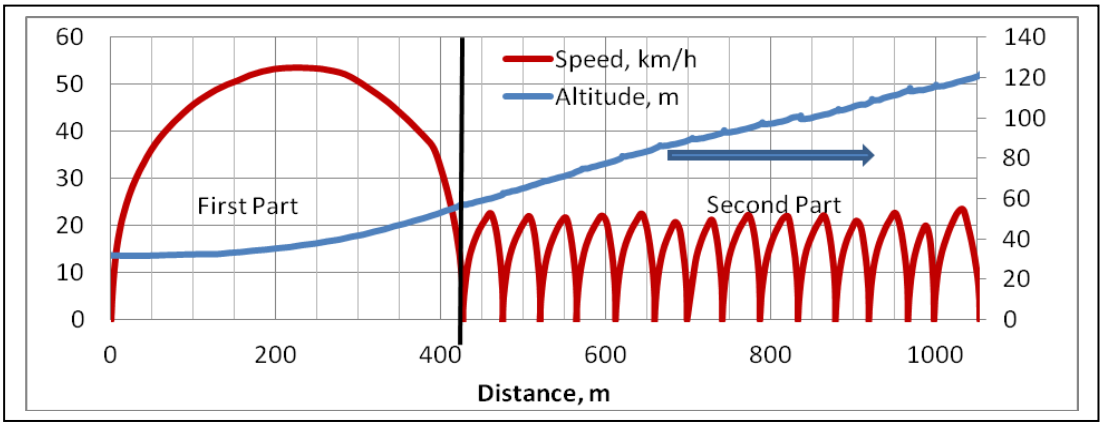

Figure 2b. Speed-distance profile of the hybrid city bus with assistance from the secondary power source.

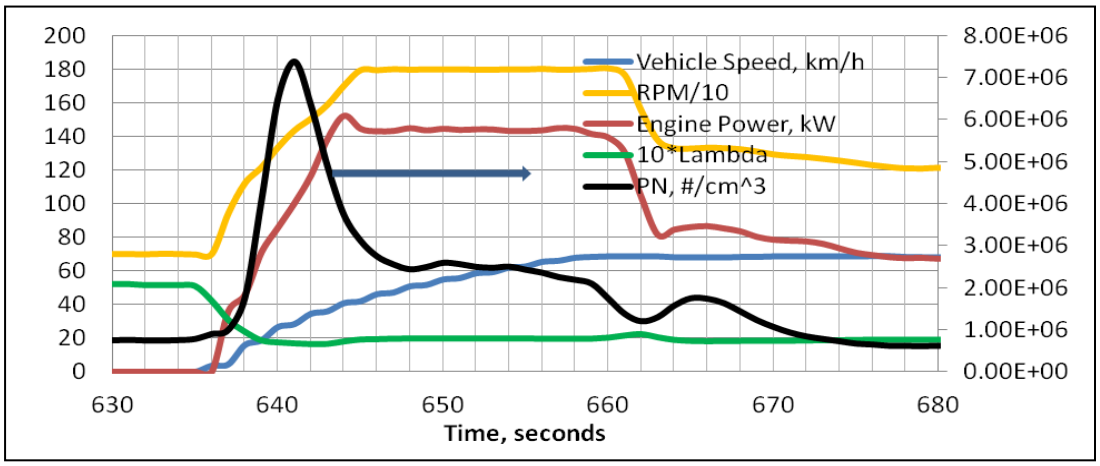

Figure 3. Effects of city bus acceleration on the engine parameters and PN emissions.

In this sense, hybridization of the city bus with a secondary power source can provide significant advantages in terms of reducing the PN emissions at its source. Since the secondary power source provides the option of providing most of demanded power during sudden accelerations of the bus, the engine accelerations from idle to higher power become very smooth with a better in cylinder combustion process. As a result, the PN emissions are reduced significantly at the source.

Figure 4a and 4b indicate the second parts of the tests that were shown in Figures 2a and 2b together with engine power, traction power and PN emissions. As can be seen from Figure 4a, if there was no power contribution to the traction power from the ultra-capacitor, accelerations of the bus from 0 to 20 km/h of speed corresponded to accelerations of the engine from idle to maximum powers, which were about 145 kW for these conditions. During these accelerations, PN emissions sharply increased from about $1.0*10^6$ to the maximum values, which were in a range from $6.5*10^6$ to $7.9*10^6$ #/cm^3 for 10 consecutive cycles. Once the engine power became steady at the maximum, PN emissions reduced to about 30% of the maximums and then during deceleration of the bus PN emissions reduced to as low as $1.0*10^6$ #/cm^3. Due to energy losses from the engine to the wheels the traction power, which is about 135 kW, remains less than the engine power for all the cycles.

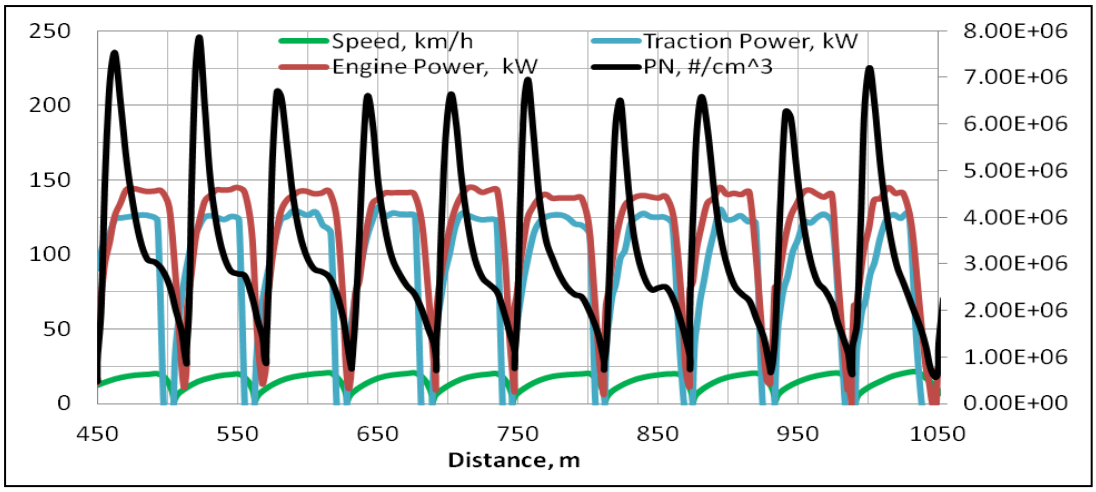

Figure 4a. Effects of city bus acceleration on PN emissions without the secondary power source assistance.

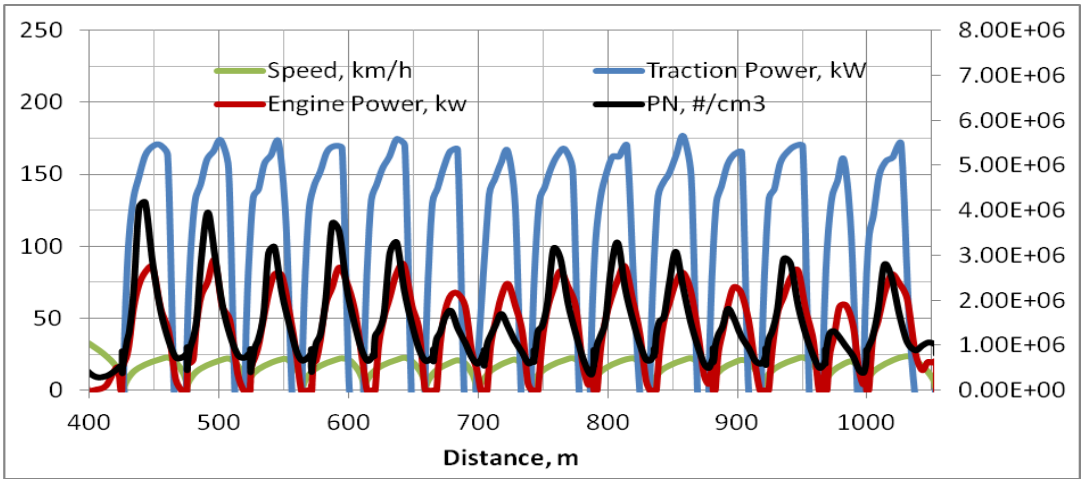

Figure 4b. Effects of city bus acceleration on PN emissions with the secondary power source assistance

When there was power assistance from the ultra-capacitor as shown in Figure 4b, while the bus accelerated from 0 to 20 km/h of speed, the traction powers immediately increased to a range from 160 to 175 kW although the engine power remained in a range from 60 to 90 kW. During these accelerations, PN emissions increased from about $1.0*10^6$ to the maximum values which were in a range from $1.5*10^6$ to $4.0*10^6$ #/cm^3. Since the engine accelerations were not as hard as that of Figure 4a, the PN emissions were reduced significantly.

Table 1 compares the PN emission characteristics of the bus with and without the ultra-capacitor contribution to the traction power. As can be seen from the table, hybridization of the city bus with an ultra-capacitor does have a strong impact on the PN emissions. Although the contribution from the ultra-capacitor significantly increased the traction energy of the bus, the reductions in averaged peak PNs, total PN per test, PN per kW-h of engine energy (PNEE), and PN per kW-h of traction energy (PNTE) were 58%, 61%, 19%, and 61%, respectively. The 61% reduction in the PNTE assumes that the ultra-capacitor is charged with regenerative braking only. This is the maximum reduction that can be achieved for the PN emissions with hybridization of the city bus under these operating conditions. With the regenerative braking, a vehicle's kinetic energy, which is normally wasted during braking can be stored in the form of electricity and used during acceleration of the bus. Therefore, the fuel consumption of the bus as well as the combustion sourced emissions including PN emissions can be reduced significantly. If there is no benefit from regenerative braking, the reduction in the PNEE, as shown in Table 1, can be only 19%. This is the minimum reduction that can be achieved for the PN emissions due to the smoother operation of the diesel engine as compared to that of the "without ultra-capacitor" assistance.

Table 1. Comparison of PN emissions without and with power contribution from the ultra-capacitor.

Operating mode	**Averaged Peak PN #/cm^3**	**Total PN #/test**	**Traction energy kW-h / test**	**PNEE #/kW-h**	**PNTE #/kW-h**
Without Ultra-cap.	$6.88*10^6$	$7.74*10^{13}$	5.06	$1.30*10^{13}$	$1.53*10^{13}$
With Ultra-cap.	$2.87*10^6$	$3.00*10^{13}$	5.10	$1.05*10^{13}$	$0.59*10^{13}$
Reduction	58%	61%	-2%	19%	61%

It is worth mentioning again that a DPF can reduce the PN emissions much more efficiently but these reductions come with additional costs. With hybridization of a city bus, beside many other advantages, the PN emissions can be reduced significantly at the source, which is very attractive, also. Beside, with such advantages in PN emissions, DPF requirement of a hybrid city busses can be significantly different from that of a conventional city bus.

Figure 5 indicates the same period for total PN and engine power. Total PN is the summation of all particles without a size limitation in the measureable range of the EEPS. As can be seen from the figure, the peaks of PN emissions and the peaks of engine power overlap.
Figures 6a and 6b show the particle size distributions at 1460 and 1320 seconds for better comparison of the size distributions for acceleration and cruising conditions of the bus. As can be seen from the figures, the acceleration condition size distributions have a bell shaped curve with 45 nm of mode and a size range approximately from 10 to 200 nm. At this condition, the engine is accelerating to reach its maximum power and total PN emissions are at the maximum.

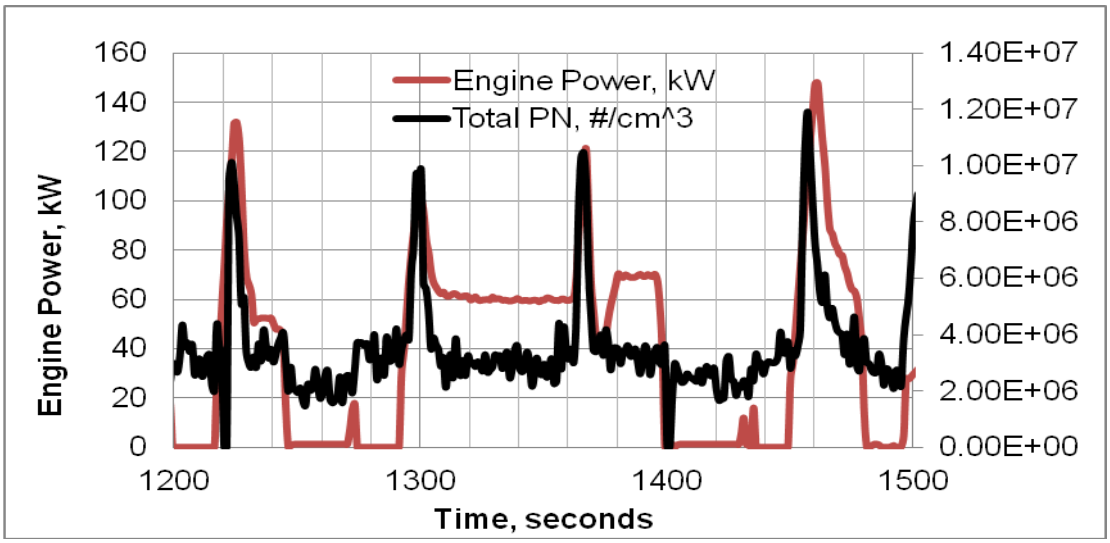

Figure 5. The effects of the engine power on total PN from 1200 to 1500 seconds of sampling period.

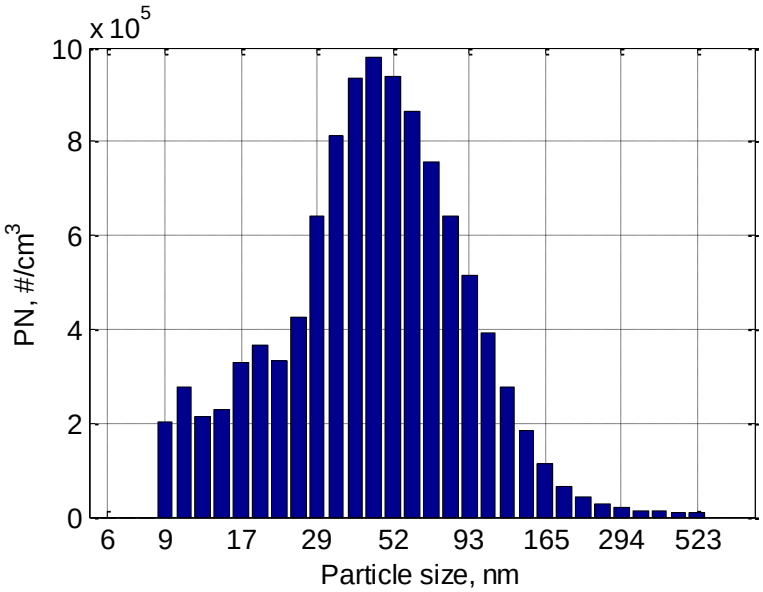

Figure 6a. Effects of engine power on particle size distribution - acceleration condition size distribution (Time= 1460th second).

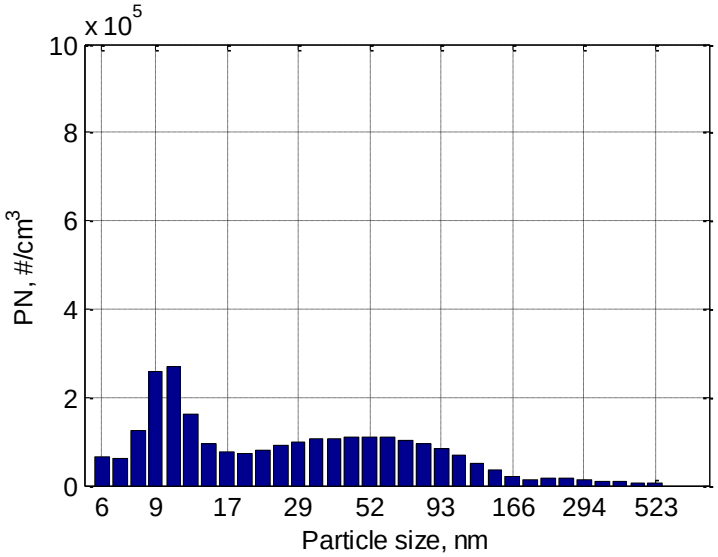

Figure 6b. Effects of engine power on particle size distribution - cruising condition size distribution (Time=1320th second).

This means that PN emissions from 20 to 200 nm are very sensitive to change in engine power. During the cruising, creeping and idling conditions, as shown in Figure 6b, PNs sized less than 20 nm are slightly dominant.

Conclusions

City bus operation in urban areas requires frequent “stop-and-go” operations which correspond to frequent accelerations of the engine from idle to higher powers. These engine accelerations are the main reason for high PN emissions due to sharp decreases of the lambda and in-cylinder turbulence. Once the engine power becomes stable at its maximum value, the PN emissions reduce dramatically to approximately 30% of the maximum PN. Therefore, the rate of increase of the engine power can be a much better indicator for PN emissions than the engine power itself.

Since most of the instantaneous traction power demands of the hybrid city bus are provided by the ultra-capacitor, the engine transients are significantly minimized. Smooth operation of the engine significantly reduces PN emissions at its source. Reduction rates in the averaged peak PNs and PNEE are 58% and 19%, respectively.

If the ultra-capacitor of the hybrid city bus is charged with regenerative braking only, then the reduction in PNTE can be as high as 61%. This is the maximum reduction rate that can be achieved under these driving conditions. The reduction comes from both the smooth engine operation due to the power assistance of the ultra-capacitor and less fuel consumption due to the regenerative braking.

During engine accelerations from idle to higher powers, PN emissions sized from approximately 20 nm to 200 nm become dominant and indicates a direct relation to sudden change of engine power. At this condition, the PN size distribution becomes a bell shaped curve with 45 nm of mode. Under cruising, creeping and idling conditions, particles smaller than 20 nm are dominant.

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