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THE IMPACT OF DIESEL BUS EMISSIONS ON AIR POLLUTION IN ULAANBAATAR AND ATTEMPT TO REDUCE IT

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ABSTRACT

The advantages of diesel engines have led it to become the only solution for heavy-duty vehicles (HDV), including city buses. Exhaust gas from diesel engines (EG) is a common environmental pollutant and carcinogenic to human health. The paper presents the results of measuring the emissions of city buses running on high sulfur fuel with and without diesel particulate filter (DPF). The study was conducted in real traffic conditions along the regular route of the city of Ulaanbaatar. The measurements were carried out using the HORIBA PEMS (Portable Emissions Measurement System) and the gravimetric method. The measured data was used to determine the actual emission levels from city buses. The actual particulate matter (PM) emissions from city buses were determined during the warm and cold seasons on a daily basis. It is found that a bus with average daily mileage of 242 km emits average of 166.155 g of PM into the atmosphere per day. This fluctuates depending on the season - 141.3 g in summer and 175.8 g in winter. The actual PM emissions of a city bus is 0.6866 g/km. The NOx concentration in the exhaust gases is 1410.94 ppm on average. As a result of 6 months of measurements, a total of 346.651 kg of soot was collected from 24 buses. Innovation: Actual on-road emissions from Ulaanbaatar buses and a cassette-type DPF system with "active" outside the bus regeneration, that can reduce conventional diesel engine PM emissions by up to 90% regardless of the sulfur content of the fuels.

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Introduction. Mongolia is world's largest landlocked country with sparse population, where road transportation is vital. Ulaanbaatar is located at an altitude of 1350 m above sea level, surrounded by four mountains. It is the coldest capital city in the world. Average temperature in summer is 30 °C, while in winter it is -25 °C [1]. Most of the transport are diesel vehicles - more than a thousand used buses with a conventional diesel engine operate in the capital, 75% of which have been in operation for more than 10 years. And they all run on high sulfur fuel. This has contributed to the critical level of air pollution, threatening the health of citizens. The most important environmental problem in the capital is air pollution. According to the results of a study of annual emissions of air pollutants by sources in Ulaanbaatar, the vehicle accounts for more than 10% of the total volume of pollution, including 70% of particulate matter (PM), 20% of nitrogen oxides and 31% of sulfur compounds emitted by city buses [2]. This statistic from the vehicles of 10% is not because there is little pollution from them, but because the background pollution is too much and therefore this problem requires every possible solution. When testing the effect of fuel sulfur concentration on emissions from heavy diesel engines using one fuel at two sulfur levels (0.01% and 0.29%), with low sulfur fuels, smaller nuclear particles virtually disappeared [3]. Soot in PM emitted from obsolete mobile sources is 75%, so reducing soot will benefit the climate [4] and reduce air pollution. Only DPF can effectively remove ultrafine particles. The cost of retrofitting is less than a tenth of avoided health care costs [5]. Emission retrofits to a diesel engine typically include the addition of an emission control device to clean the waste exhaust gas. However, almost all emission control devices are very sensitive to the sulfur content of the fuel. Sulfur reacts with water vapor from the exhaust to form corrosive acids and leads to multiple carbon deposits. The diesel particulate filter clogs much more slowly when low-sulfur fuel is burned [6]. The need to limit sulfur in fuel has been written in many research papers on this issue, and the permissible limits are indicated in regulatory documents. According to the analysis results, the sulfur content in diesel fuel used in the country ranges from 1400 ppm to 3000 ppm [7], which limits the possibility of direct localization of technologies currently used in developed countries. In search of opportunities and methods to reduce emissions from buses running on high sulfur fuels, experimental studies were carried out in two stages: pilot and in-depth. At the pilot stage, to assess the feasibility of hypothesis put forward about the need for at least one additional cleaning technology that would effectively reduce the emission of black smoke from an outdated conventional diesel engine running on high sulfur fuel, we alternatively installed a diesel oxidation catalyst, DPF with catalyst and two types of filters without catalyst and measured the distance traveled until a certain backpressure limit was reached. Of these devices, DPF from SiC without catalyst, with a porosity of 200 pores/in^2 worked at the largest distance, was selected and used for further experiments. The selected method of filter cleaning is periodic replacement of the used filter with a cleaned one, e.g., "Active regeneration". This technology is used for both new engines and in-use engines retrofitting [6]. A distinctive feature of the study is continuous measurements of toxic emissions in real conditions while running the buses using the PEMS on-board measuring system. It is the first attempt to retrofit a conventional diesel engine in the current technical and fuel conditions of Mongolia.

The significance of study is that the actual road PM of city buses are determined, which can be used in the subsequent studies to reduce emissions and demonstrate the possibility of real reduction of black smoke by retrofitting conventional diesel engines of buses with DPF, which make up 98% of the total bus fleet.

Testing methodology and instruments. One city bus was retrofitted with a DPF system (Fig. 1), consisting of three working and three replaceable filters, a distribution pipe, a pressure sensor, a display with an audible signal, a bypass valve. DAEWOO BS106 bus was used in the experiment as shown below.

Table 1. Technical specifications of the tested bus.

Engine displacement	11051cm^3
Number of cylinders	6
Compression ratio	17.1
Aspiration	Atmospheric, naturally
Emission rate	Pre-Euro
Exhaust gas treatment system	No
Maximum power	165kW@2200 min^{-1}
Maximum torque	800 Nm@1400 min^{-1}
Curb weight	9015 kg
Manufacture year	2009

Fig. 1. DAEWOO BS106 bus.

Fig. 2. DPF installed on DAEWOO BS106 bus

To simulate the conditions of daily operation of buses on urban routes, the bus was loaded to a nominal capacity of 70 people weighing 70 kg each. In real-world driving tests, the HORIBA PEMS measuring system measured and recorded the following parameters at a frequency of 0.5 seconds:

- PM concentration (MEXA-130S opacimeter)
- NOx concentration (MEXA-720 NOx analyzer);
- O_2 concentration (oxygen sensor);
- Engine revolutions per minute (RPM);
- Atmospheric pressure, temperature and humidity;
- Position and speed of the bus - GPS system.

Fig. 3. The bus load was equal to 70 people

Also measured the backpressure in the filter system and the length of the path before the need for filter replacement. Emission measurements were carried out on urban and suburban routes. The choice of the route for the study was dictated by the real conditions of bus use for a typical urban area, varied mileage on major highways, roads in residential areas (Fig.4) with high variability of acceleration and traffic congestion, which allows the analysis of emissions in a wide range of conditions.

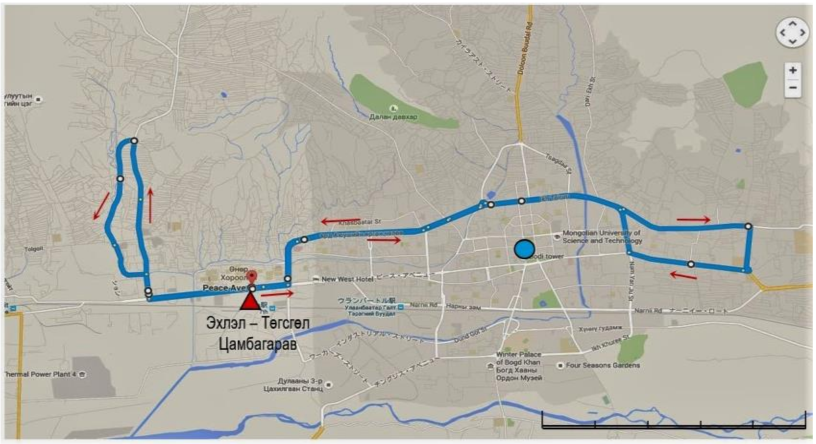

Fig. 4. City routes used for road tests

The second route is suburban, the number of stops is less, its length on one side is 23 km (Fig. 5).

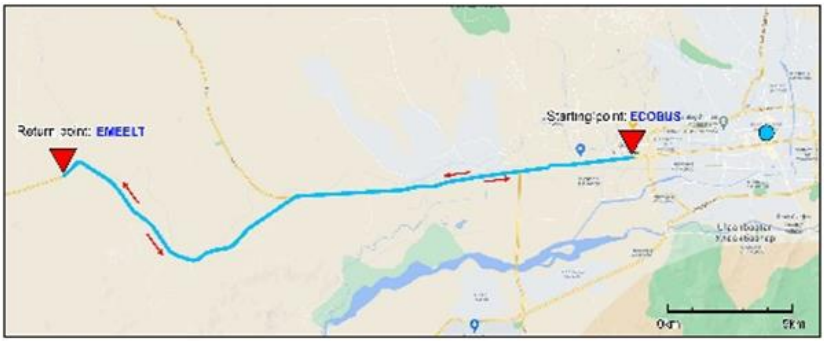

Fig. 5. Suburban route used for road tests

At the second stage of the experiment, an additional 24 city buses were retrofitted with the same DPFs as in the first stage of the study and were operated in real conditions of public services in the city on a variety of routes in normal mode in warm and cold seasons, without setting limits on sulfur content in fuels, used any diesel fuel provided by the market.

By the end of the day, when each bus entered the fleet, a designated employee replaced the filter elements for regenerated ones, while keeping a separate log for each bus, where he recorded filters own number and the mass of three clean filters, as well as the odometer reading. And then the mass of each uncleaned filter was determined gravimetrically, the value was entered in the logbook, and the difference in the filter masses before and after cleaning determined the mass of filtered soot with this filter, and the sum of soot masses from three filters of one group determined the total mass of filtered soot from this bus per day and filled in the magazine.

Thus, the actual emissions of city buses were experimentally investigated over a period of six months. The opacity of EG were measured for all buses before and after installation to assess the impact of DPF.

Results. As a result of static processing of the data obtained from the on-board measuring system of the EG, the equations of the regression model of PM emission were obtained depending on the technical speed of the bus and the engine RPM with and without DPF.

Fig. 6. Each filter has its own number

Fig. 7. Filter mass before regeneration

Fig. 8. Filter mass after regeneration

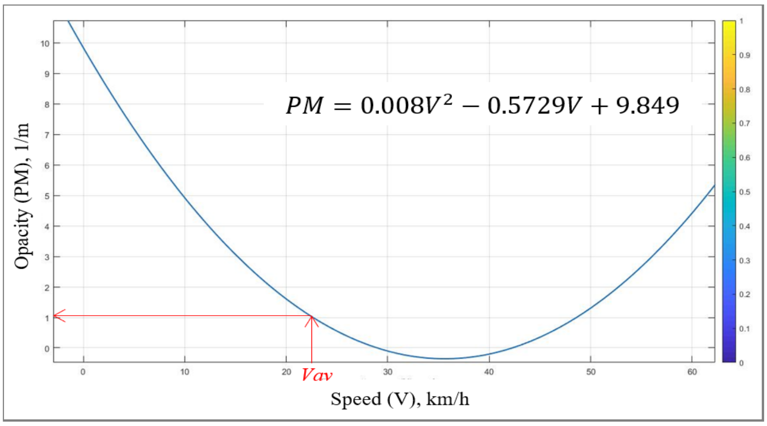

Fig. 9. PM and technical speed relation for the bus without DPF

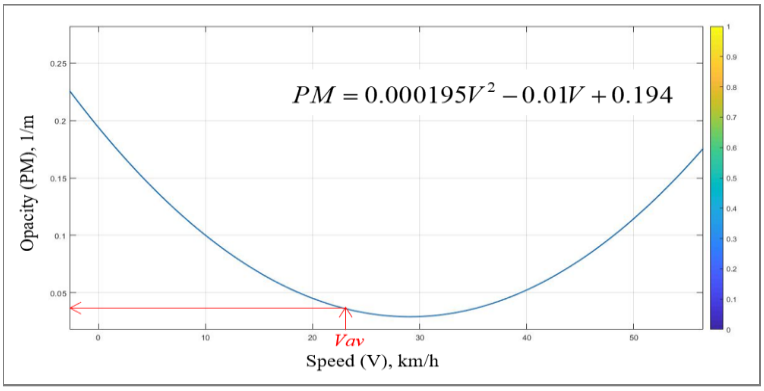

Fig. 10. PM and technical speed relation for the bus with DPF

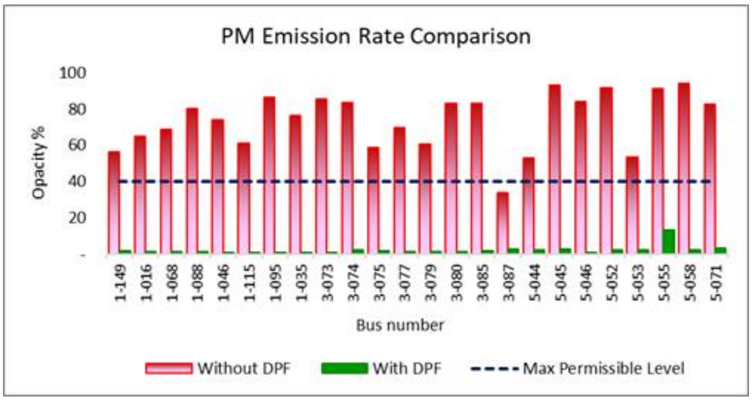

Fig. 11. Opacity of EG comparison - before vs. after retrofitting

The opacity of exhaust gases of buses decreased by an average of 97% (Fig. 11).

Under real operating conditions of a bus without DPF the average exhaust opacity is K = 3.91 m^{-1} and the NOx concentration is 1410.94 ppm. The average technical speed of bus in the city was 22.48 km/h.

A bus with an average daily mileage of 242 km was found to emits 166.155 g of PM into the city's atmosphere on average per day, with 141.3 g in summer and 175.8 g in winter. The actual PM of the city bus is 0.6866 g/km.

Backpressure is the exhaust pressure at the outlet of the exhaust manifold, which is numerically equal to the pressure drop of the exhaust gases throughout the entire exhaust system. Boosted backpressure could lead to more fuel consumption and could adversely affect engine performance, therefore it is severely limited. The experimental bus passed in December, at an ambient temperature of minus 21 °C, along the urban route of 302 km, and at the same time a backpressure of 22.5 kPa was formed, and on the suburban route at 294 km 17.5 kPa, which is approximately equal to 75 and 58 percent of the recommended limit backpressure for this diesel model, respectively.

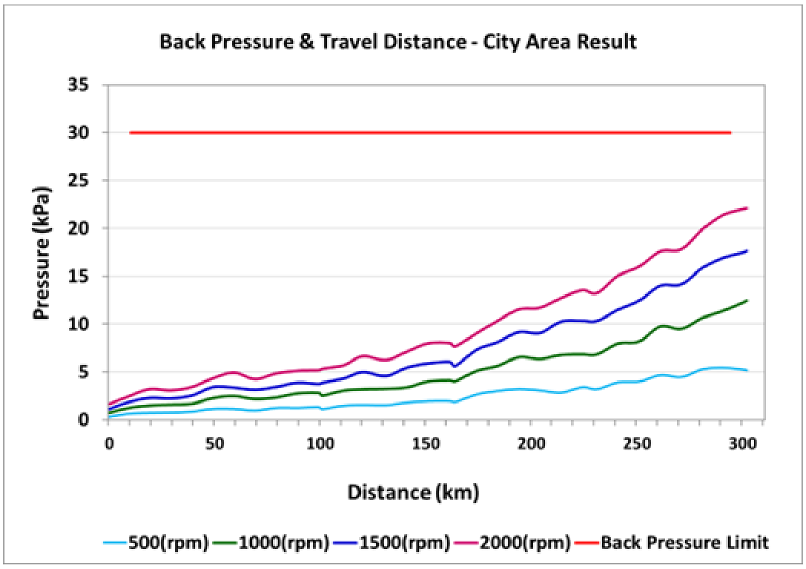

Fig. 12. Backpressure rate when travelling in the city

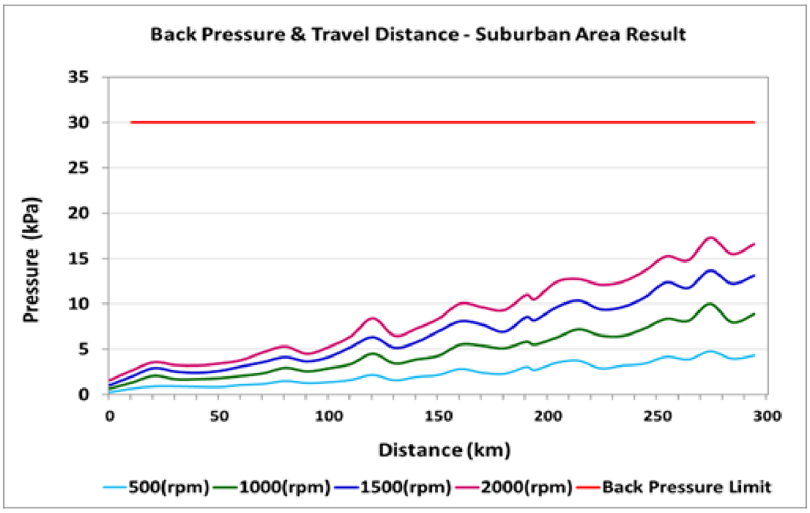

Fig. 13. Backpressure rate when travelling in the suburban area

As a result of measuring the distance traveled without changing the filter, the bus traveled 300 km with an exhaust system backpressure of 60% -70% of the recommended limit, which means that the bus does not need to replace the clogged filter with a clean one during working hours (Fig. 12 and 13).

Furthermore, the study result indicates that the opacity of EG was 1.1 $m^{-1,}$ with an average technical speed of the buses of 22.48 km/h without DPF (Fig. 9). Conversely, with DPF opacity of EG was 0.03 m^{-1} (Fig. 10), which ultimately decreased by 97.3%.

In just 6 months 346.651 kg of soot was filtered from 24 buses by using DPF. These results are indicative of the significance and positive performance of the selected particulate filters.

Discussions. As a result of our research, we see the possibility of reducing PM emissions of a city bus with a conventional diesel engine running on high sulfur (1000 ppm - 2000 ppm) fuel by retrofitting them with a wall-flow DPF from SiC.

A number of large projects for the modernization of diesel buses have been implemented around the world, among them projects in Berlin, Switzerland, also in Santiago de Chile, Bogota and Tehran [1]. Such modernization was usually preceded entirely by country [2] or partially for the target user [3] by reducing the sulfur level in the fuel. The use of low sulfur fuel in combination with emission control devices reduces the amount of selected pollutants in the exhaust gases of heavy diesel engines without a significant increase in other toxicants [4]. Baranescu (1988) and Lange (1991) found a strong correlation between sulfur content of fuel and total PM levels. The less sulfur in the fuel, the less SO_2 is generated in the engine, and therefore less SO_4, which in turn contributes to the formation of total PM [4]. Test results from the European Particle Measurement Program have demonstrated that wall-flow filters are effective in reducing diesel particles by three orders of magnitude with a filtration efficiency of 99.9% [2]. The technical level of diesel engines is assessed in terms of fuel efficiency and environmental performance [11].

In this experiment, the filtration efficiency is 97% at an average technical speed. The actual road PM emissions from public transport buses in Ulaanbaatar were also determined.

During the experiment, the backpressure in the DPF reached the manufacturer's specified limit in one and a half two shifts, which dictated the replacement of the filter after each shift and the use of the regeneration method outside the bus. In older conventional diesel engines, high emission levels and no change in emission levels are maintained when using fuels with different sulfur contents [12]. Therefore, even if the sulfur level in the fuel can be reduced, the operation of buses with conventional diesel engines and not meeting the Euro I emission thresholds will continue to make a significant contribution to the pollution of the Ulaanbaatar air basin. One way out of this situation may be to equip these buses with cassette type diesel particulate filters. While such upgrades are costly, they are not comparable to the health burden on city dwellers.

Conclusion. Twenty-four buses retrofitted with DPF over six months at a fleet utilization rate of 86.6, an average of 13.615 kg of soot was collected from each bus, for a total of 346.651 kg. Actual daily PM emissions from bus in Ulaanbaatar are 166.155 g on average, and emissions per kilometer are 0.6866 g/km, which is 14.43% higher than Euro I standard.

As a result of comparative analysis of monthly measurements of the warmest - July and the coldest - December months, it was found that the average daily soot emission of one bus is 141.3 g in July and 175.8 g in December, and winter emission exceeds summer by 24.4%.

As a result of on-board emissions measurements, it was revealed that it is possible to reduce PM emissions of city buses by 90% or more by retrofitting them with a suitable DPF without deteriorating the technical condition of the diesel engine for a long time under the fuel and temperature conditions of the city of Ulaanbaatar.

Practical significance: The developed DPF system can be applied on various types of vehicles with diesel engines, including trucks, road-building and agricultural vehicles, forklifts and backup generators in enclosed spaces, underground mines, etc., regardless of the sulfur content in the used fuel.

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