THE RESEARCH ON THE POSSIBILITY OF REDUCING EMISSIONS OF CITY BUSES RUNNING ON HIGH SULFUR FUEL USING A PARTICULATE FILTER

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Abstract: Diesel engines are widely used in heavy vehicles, including public buses, due to their many advantages. Diesel engine exhaust is a ubiquitous environmental pollutant and carcinogenic. The article presents the results of measuring the emissions of city buses running on high sulfur fuel with and without a diesel particulate filter (DPF). The study was conducted by the HORIBA PEMS (Portable Emission Measurement System) in real traffic conditions on a regular route of Ulaanbaatar. The data obtained was used to determine the real-world emissions of conventional diesel engines of city public buses and to evaluate the effectiveness of the selected particulate filters. Retrofitting a conventional diesel engine with a silicon carbide (SiC) particulate filter can significantly reduce exhaust black smoke. Innovation: PM and NOx mathematical model equations have been estimated as a function of the bus technical speed and engine revolution with and without DPF.

Key words: particulate matter, diesel particulate filter, silicon carbide, real-time on-board measurement, the real-world emissions, fuel sulfur.

ИССЛЕДОВАНИЕ ВОЗМОЖНОСТИ СОКРАЩЕНИЯ ВЫБРОСОВ ГОРОДСКИХ АВТОБУСОВ, РАБОТАЮЩИХ НА ТОПЛИВЕ С ВЫСОКИМ СОДЕРЖАНИЕМ СЕРЫ И ИСПОЛЬЗУЮЩИХ САЖЕВЫЙ ФИЛЬТР

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Аннотация: Дизельные двигатели широко используются в большегрузных транспортных средствах, в том числе в общественных автобусах, благодаря их многочисленным преимуществам. Выхлоп дизельного двигателя является повсеместным загрязнителем окружающей среды и канцерогенным для человека. В статье представлены результаты измерения выбросов городских автобусов, работающих на высокосернистом топливе с сажевым фильтром (СФ) и без него. Исследование проводилось с помощью HORIBA PEMS (Портативная система измерения выбросов) в реальных условиях движения на регулярном маршруте Улан-Батора. Полученные данные использовались для определения фактических выбросов городских автобусов и оценки эффективности выбранных сажевых фильтров. Дооснащение дизеля традиционной конструкции сажевым фильтром из карбида кремния (SiC) может значительно снизить дымность выхлопных газов. Инновация: Уравнения математической модели твердых частиц (PM) и оксидов азота (NOx) были оценены как функция технической скорости автобуса и частоты вращения двигателя с СФ и без него.

Ключевые слова: твёрдые частицы, сажевый фильтр, карбид кремния, портативная система измерения выбросов, бортовые измерения в режиме реального времени, сера в топливе.

Introduction. The results of a study of annual emissions of air pollutants' sources in Ulaanbaatar indicates that the vehicle accounts for more than 10% of the total pollution, of which city buses emit 70% of PM, 20% of nitrogen oxides and 31% of sulfur compounds [1]. The vehicle driven 10% of pollution may seem to be small proportion of the total pollution, however, the volume of total pollution is considerably high, thus it requires every possible solution to reduce vehicle emissions. Almost all buses run on diesel engines with outdated design - 75% of them have been in operation for more than 10 years. 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 [2]. Soot in PM emitted from obsolete mobile sources is 75%, so reducing soot will benefit the climate [3] and reduce air pollution. Only DPF can effectively remove ultrafine particles. The cost of retrofitting is less than a tenth of health care costs [4]. Emission retrofits to a diesel engine typically include the addition of an emission control device to clean the waste exhaust gas (EG). 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 [5]. 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 1200 ppm to 3000 ppm, 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 diesel 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/in2 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 older engines retrofitting [5]. A distinctive feature of the study is continuous measurements of toxic emissions in real conditions while running the buses using the HORIBA PEMS on-board measuring system. The significance of the study is that the real-world emissions 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 DAEWOO BS106 buses with DPF, which make up 98% of the total bus fleet.

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

Table 1

Technical specifications of the tested bus [6]

Engine Model	DE12
Engine Displacement (cc)	11051
Number of Cylinders	6
Compression Ratio	17.1
Aspiration	Atmospheric, naturally
Exhaust Gas Treatment System	No
Max Power (kW@RPM)	165kW@2200 min^{-1}

Continuation of the table 1

Max Torque (Nm@RPM)	800 Nm@1400 min^{-1}
Manufacture Year	2009
Bus Curb Weight (kg)	9015 kg

Figure 1. DAEWOO BS106 bus

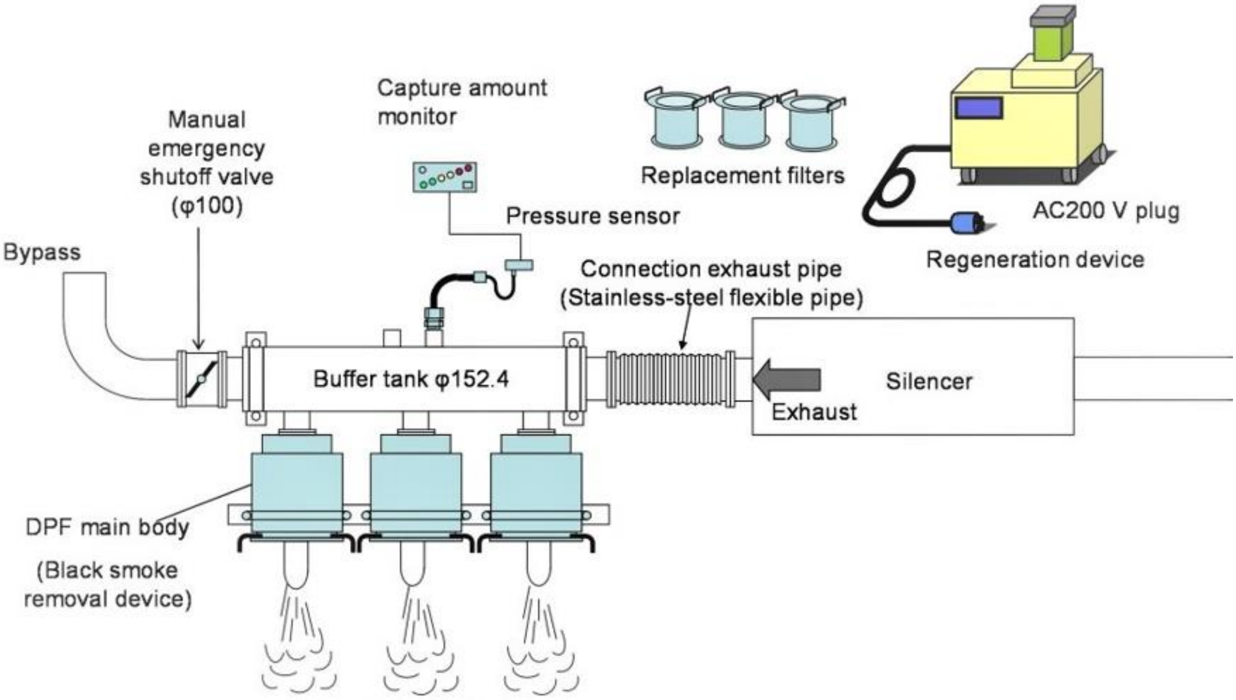

Figure 2. Cassette type DPF system structure

Figure 3. DPF system 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.

Figure 4. The bus load was equal to 70 people

In the experiment, a cassette-type DPF system was used, consisting of three SiC filters, Φ165mm x 150.5mm, with a wall-flow and “active” regeneration outside the vehicle. 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 (Figure 5) with high variability of acceleration and traffic congestion, which allows the analysis of emissions in a wide range of conditions. The second route is suburban, the number of stops is less, its length on one side is 23 km (Figure 6).

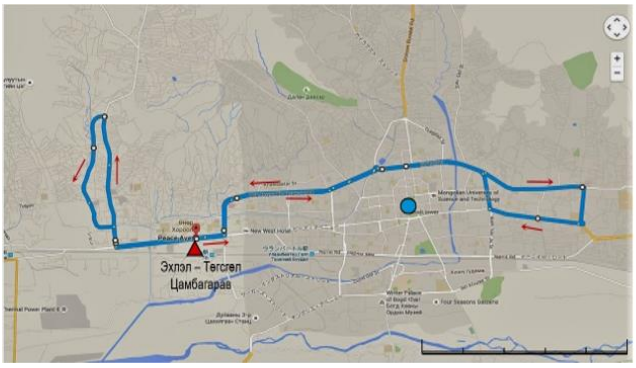

Figure 5. City routes for road tests

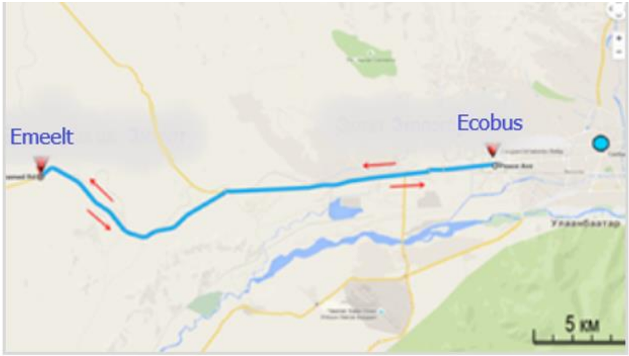

Figure 6. Suburban route for road tests

Also measured the backpressure in the filter system and the length of the path before the need for filter replacement. Every 10 km of run, over a total of 1284 km, the backpressure was measured at engine speed of 500, 1000, 1500 and 2000 rpm.

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.

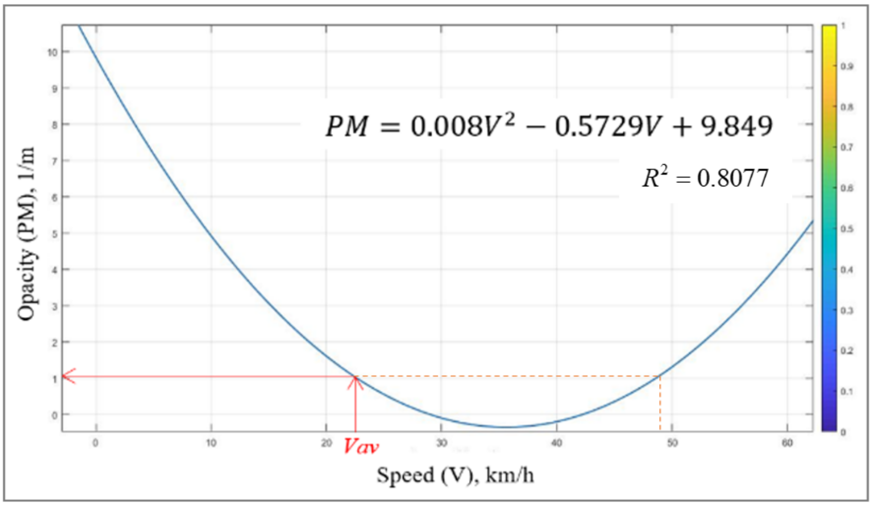

Figure 7. PM and technical speed relation for the bus without DPF

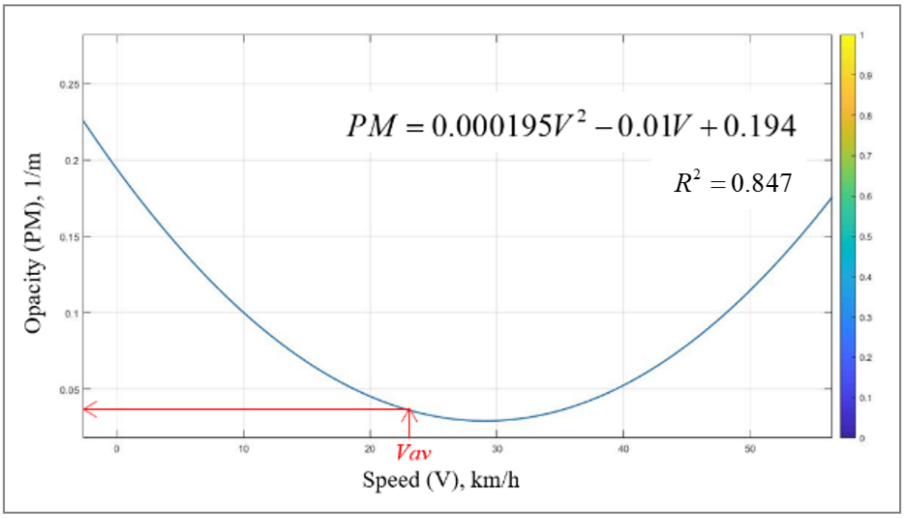

Figure 8. PM and technical speed relation for the bus with DPF

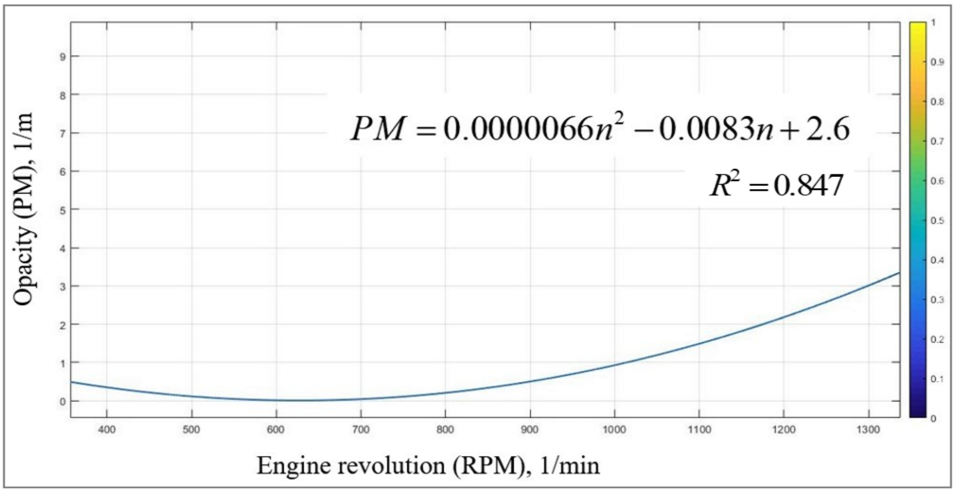

Figure 9. PM and engine RPM relation for the bus without DPF

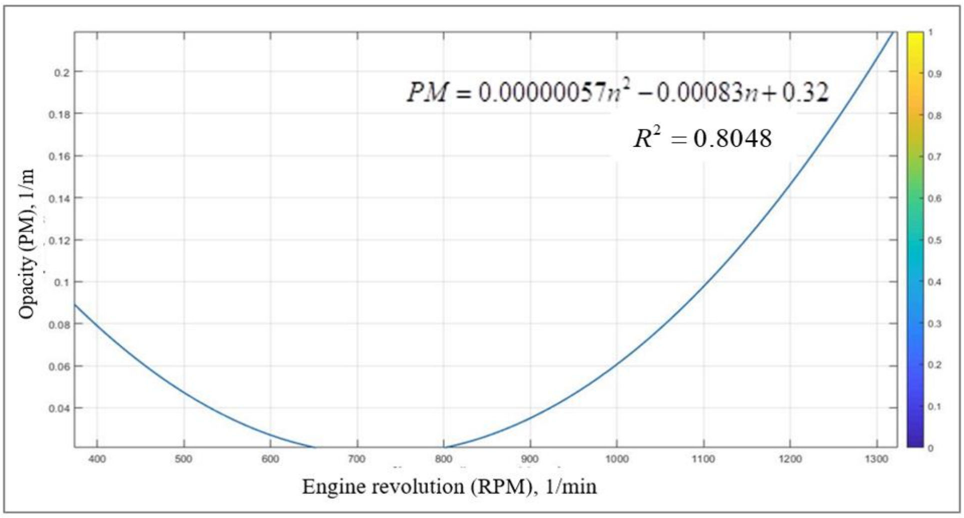

Figure 10. PM and engine RPM relation for the bus with DPF

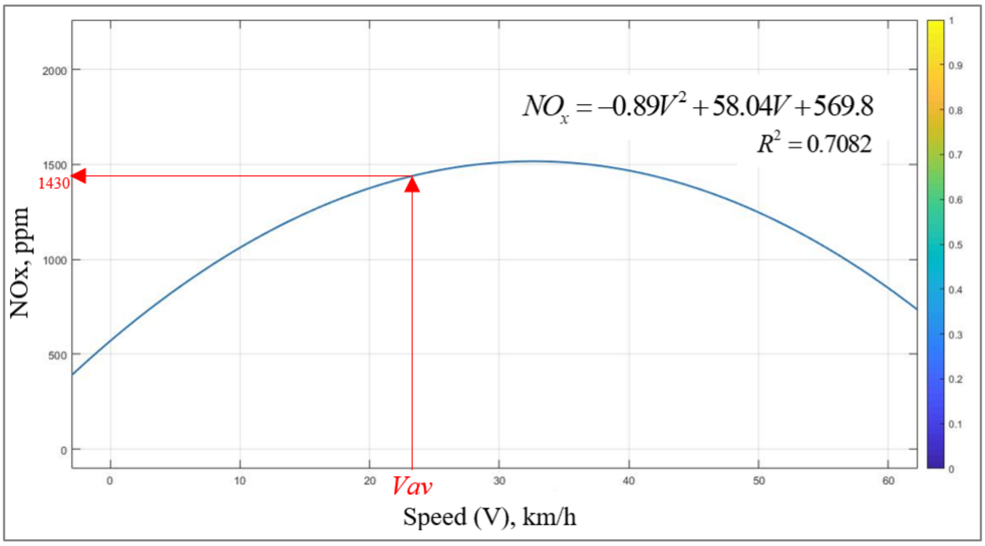

Figure 11. NOx and technical speed relation for the bus without DPF

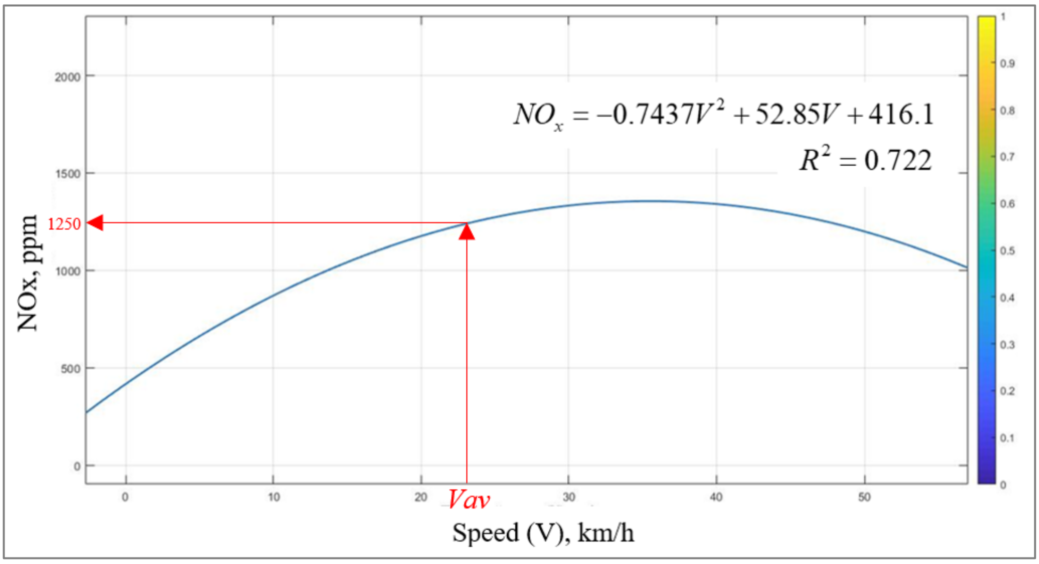

Figure 12. NOx and technical speed relation for the bus with DPF

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 operated 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 (Figure 13), and on the suburban route at 294 km 17.5 kPa (Figure 14), which is approximately equal to 75% and 58% of the recommended limit backpressure for this diesel model, respectively. The average bus speed in the city was 22.48 km/h.

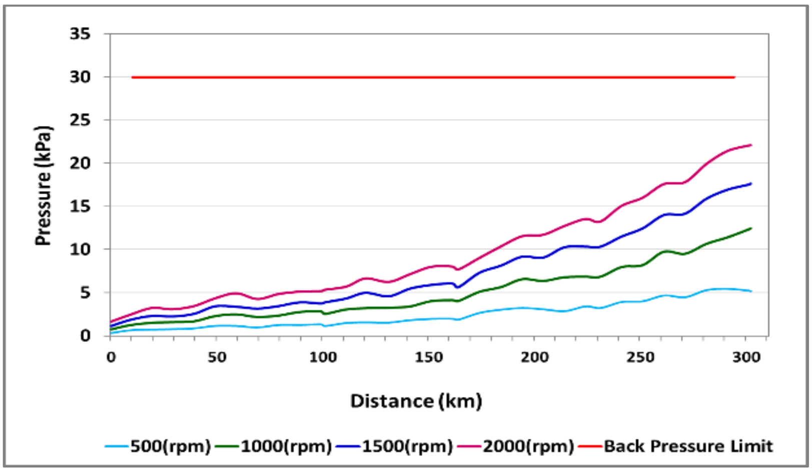

Figure 13. Backpressure rate when travelling in the city

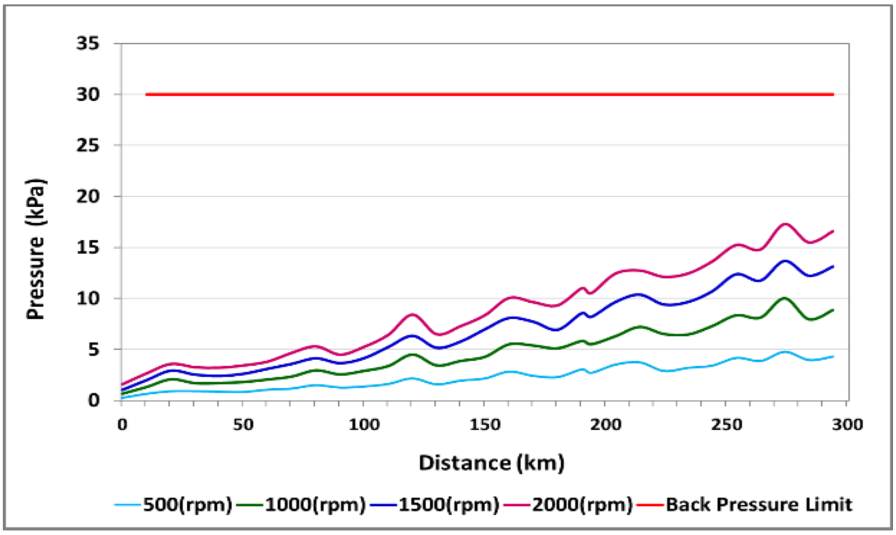

Figure 14. Backpressure rate when travelling in the suburban area

As a result of measuring the distance traveled without changing the filter, the bus traveled 300 km with an exhaust system backpressure of 58%-75% of the recommended limit, which means that the bus does not need to replace the clogged filter with a clean one during working hours (Figure 13 and Figure 14). Furthermore, the study result indicates that the EG opacity was 1.1 $m^{-1,}$ with an average speed of the buses of 22.48 km/h without DPF (Figure 7). Conversely, with DPF exhaust gas opacity was 0.03 m^{-1} (Figure 8), which ultimately decreased by 97.3%. These results are indicative of the significance and positive performance of the selected particulate filters.

DPF reduces NOx concentration at average technical speed of buses compared to concentration without DPF by 12.6% (Figure 11 and Figure 12).

Discussion. 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 (1000-2000 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 [7]. Such modernization was usually preceded entirely by country [8] or partially for the target user [4] by reducing the sulfur level in the fuel. The use of low sulfur fuels in combination with emission control devices reduces the number of selected pollutants in the EG of heavy diesel engines without significantly increasing other toxicants [9]. Baranescu (1988) and Lange (1991) found a strong correlation between sulfur content 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 [9]. Test results from the European Particle Measurement Program have demonstrated that wall-mounted filters are effective in reducing diesel particles by three orders of magnitude with a filtration efficiency of 99.9% [8]. In this experiment, the filtration efficiency is 97% at an average speed. The actual road PM emissions from public transport buses in Ulaanbaatar were also determined. The technical level of diesel engines is assessed in terms of fuel efficiency and environmental performance [10].

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 [11]. Therefore, even if the sulfur level in the fuel can be reduced, the buses operating on conventional diesel engines will not meet the Euro I emission thresholds, 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, SiC diesel particulate filters. While such upgrades are costly, they are not comparable to the health burden on city dwellers.

Conclusion. As a result of on-board measurements of emissions from conventional diesel engines of city buses running on high sulfur fuel, it was revealed that it is possible to reduce particulate emissions by 90% or more by retrofitting them with a silicon carbide wall flow particulate filter without deteriorating the technical condition of the diesel engine under the fuel and temperature conditions of the city of Ulaanbaatar. A 97% reduction in particulate emissions at average technical speed indicates the effectiveness of the DPF application.

DPF has little effect on NOx emissions.

At the same time, it was revealed that the technical speed of non-modernized buses from 22.48 km/h to 48.5 km/h corresponds to the minimum PM emission, which is less than 1.1 m^{-1}. This indicates that an increase in the overall speed of traffic can significantly reduce air pollution from vehicles.

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.

It is necessary to study easy and reliable methods of regeneration.

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