

## ENVIRONMENTAL BENEFITS OF THE SCR SYSTEMS: A CASE STUDY OF THE LUBLIN CITY TRANSPORT

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### ABSTRACT

Standards linked with the environmental protection and vehicles are increasingly restrictive. EURO VI standard and regulations define the acceptable limits for exhaust emissions of new vehicles sold. Because of that, Selective Catalyst Reduction systems are used in a new vehicles with the heavy-duty type engines. This paper presents a study of the SCR system in public transport vehicles of the Municipal Transport Company (MPK) in Lublin, Poland. The tests were performed to study the power consumption of the SCR (the urea applicator into the catalyst) and calculate the results per unit of fuel. The amount of fuel for the Solaris Trollino 12 trolleybus was estimated and the energy demand found was of the order of 343 kWh/year. This gives low diesel fuel consumption, i.e. only 34.3 litres per year. The study also shows a graph of the daily demand of energy by the SCR system in public transport vehicles.

**Keywords:** MPK, SCR system, nitrogen oxides, heavy-duty diesel engines

## INTRODUCTION

Currently, one of the most important issues linked with the environment protection is the reduction of exhaust gas in vehicles. The European emissions standard sets out the requirement of acceptable exhaust emissions for the new vehicles sold in the European Union in a series of European Directives [13, 7]. Over the years, these standards have become more and more stringent. The biggest problem are diesel engines, which produce the most dangerous pollutions for humans: nitrogen oxides NO<sub>x</sub> and particulates. Solutions to reduce the harmful substances in the air include: multiple fuel injection per cycle, exhaust gas recirculation valves, DPF (diesel particulate filter), modification of the combustion process and implementing the external SCR (Selective Catalytic Reduction) system. Regulations about reducing exhaust in Europe for new heavy-duty type engines are based on the Euro I ... VI norms [13, 7, 11, 4].

This paper presents a study of the SCR system in public transport vehicles of the Municipal Transport Company (MPK) in Lublin, Poland.

### Permissible levels of NO<sub>x</sub> concentration and the impact on living organisms

Permissible value of the NO<sub>x</sub> concentration in the air with regard for plant protection is 30 µg/m<sup>3</sup> during the year, and taking into account people protection – 40 µg/m<sup>3</sup> during year [15]. NO<sub>x</sub> can cause the destruction of green cells and leaf fall, and for humans: pulmonary and cardiac problems and cancer. Nitrogen oxides also absorb sunlight, consequently causing photochemical smog. Nowadays, the main sources of NO<sub>x</sub> in Poland are: combustion processes in the production and transformation of energy (approx. 30%), road transport (approx. 30%), other vehicles and equipment, combustion processes, manufacturing and agriculture [5]. It therefore seems necessary

for diesel-powered vehicles to use additional systems reducing the NOx in exhaust gas.

In Poland the permissible concentration of nitrogen oxides in ambient air (as NO<sub>2</sub>) is:

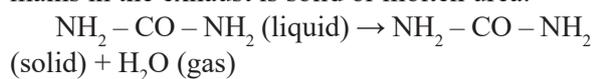
- 150 µg/m<sup>3</sup> on average per day
- 500 µg/m<sup>3</sup> once within 30 minutes
- in areas of special protection these figures are, respectively, 50 and 150 mg/m<sup>3</sup> [13]

According to the current Euro VI standards, the emission limit for heavy-duty type vehicles are: at steady-state work of 0.40 g/kWh of NOx, and at transient work 0.46 g/kWh NOx. Durability of emissions for vehicles above 16 tonnes should not exceed 700 thousand km or 7 years [6].

### Description of phenomena which lead to NOx reduction in the SCR system, using an aqueous solution of urea

AdBlue is an aqueous solution of urea (containing 32.5%), obtained from technically pure urea (without the addition of other materials), and deionised water. It is used in SCR systems, where NOx can be reduced to nitrogen and water. AdBlue is injected into the mixture of exhaust gases in counter current to the catalyst. Depending what kind of a catalyst is used, the range of the temperatures in which the reduction can occur, usually equals 300–400 °C. The system can be divided into four groups of processes [10, 3]:

When AdBlue is injected into the exhaust, during the first step water evaporates and what remains in the exhaust is solid or molten urea:



Then the thermal decomposition of urea can be observed, by the chemical degradation into the isocyanic acid HNCO and ammonia NH<sub>3</sub>. The melting point of urea is approx. 132 °C, but slow detectable degradation starts from 80 °C [1, 8]:



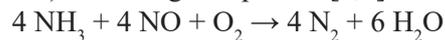
Ammonia can be received as a result of HNCO hydrolysis. Although isocyanic acid is a very stable chemical compound in gaseous state, when oxide catalysts are used and in the presence of steam, the reaction is exothermic [9]:



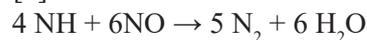
Spontaneous HNCO hydrolysis occurs very slowly. By using a catalyst it is possible to receive a sufficient reaction rate in the temperature range

of 180–550 °C. Active catalyst components are, for example, Al<sub>2</sub>O<sub>3</sub> or TiO<sub>2</sub> [2, 12]. The use of an initial oxidation catalyst causes oxidation of NO to NO<sub>2</sub> and accelerates the SCR reaction. The acceleration of these reactions is only up to 50% of the share of NO<sub>2</sub>. Above 50%, the efficiency of NOx reduction drops significantly [10].

The mechanism of selective reduction with ammonia consists in the catalytic conversion of nitrogen oxides in the presence of oxygen is relatively slow (the rate of the reaction increases from 200 °C) according to equation [1,8]:



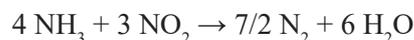
Reaction without oxygen is much slower and is not relevant in the case of oxygen-rich exhaust gas [9]:



Conversion of part of NO<sub>2</sub> takes place without the participation of oxygen from the exhaust, in a faster-occurring reaction also at a temperature below 200 °C:



The reduction of NO<sub>2</sub> is much slower than the above-described reactions, according to the equation:

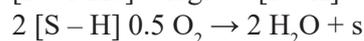
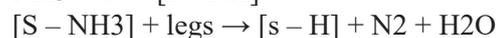
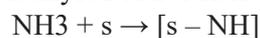


The literature also gives another reaction scheme, according to Künkel [10]:

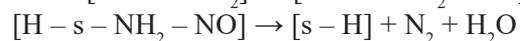
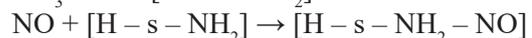
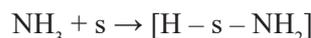


The reaction of reducing NOx in SCR systems is described in the literature using the following two methods [8, 3]:

- the Eley-Redeal mechanism, based on the reaction of ammonia with the adsorbed NO from the gas state, while oxygen regenerates the catalyst's active sites:



- an intermediate compound like nitrosamine is formed:



Generally, the reaction rate is described by the relationship:

$$r_{\text{NO}} = k_c \cdot c_{\text{NO}}^\alpha \cdot c_{\text{NH}_3}^\beta \cdot c_{\text{O}_2}^\gamma \cdot c_{\text{H}_2\text{O}}^\delta$$

The literature contains many studies that suggest that the magnitudes for the respective compounds mentioned in the equation vary widely [1, 8]. In simple terms, for catalysts based on vanadium or Cu zeolites, a simplified notation can be assumed in the form of:

$$r_{\text{NO}} = k_c \cdot c_{\text{NO}}^\alpha$$

It must be concluded that the reaction kinetics depends both on the type of the catalyst and the reaction conditions.

### Energy consumption in the SCR system

In analysing the environmental impact, one cannot ignore the energy consumption of the SCR system. The study was conducted in collaboration with the Municipal Transport Company in Lublin, Poland. The tests were performed to study the power consumption of the SCR (the urea applicator into the catalyst) and calculate the results per unit of fuel. The research object was the modern hybrid trolleybus Trollino 12 Solaris. The vehicle is equipped with a series drive from Kirsch, which consists of an asynchronous motor, a generator and a diesel engine. The rated power of the main drive is 175 kW. The trolleybus is also equipped with a pantograph system, which automatically connects with an overhead catenary wire. The combination of electric motor and diesel engine allows to expand the area along which the vehicle can move, for example to outside urban areas. The study used a factory

Power Analyser 6315 from Kyoritsu. The device was connected to the vehicle's electrical system, so that it was possible to collect data of the current energy consumption by the SCR system. The main aim of this device was the acquisition of data, i.e.: power consumption, the voltage at the terminals of the SCR system and the indication of instantaneous power. The device made measurements at 1-second intervals and stored all parameters in an SD card. In order to increase the accuracy of measurement, two analogue high-definition voltage outputs with a range of 0–5 V were used. In order to measure currents, a linear current-voltage converter ACS712–20A based on the Hall effect was used. Figure 1a shows the Kyoritsu analyser, installed inside the control box of the main drive. Figure 1b shows the location of the control box inside Trollino 12 vehicle.

In order to analyse the power consumption by SCR system, the vehicle was first driven along route No. 160, to be then redirected to route No. 20. Both routes are located within the city of Lublin. The routes were chosen to check how the system behaved in a combined cycle mode (steady-state and transient).

The test results for the SCR system will be presented for route No. 20, which was divided into three sections:

- a) the ride of 4.03 km, powered by the hybrid drive (Dębówka – Al. Raławickie) (Fig. 4);
- b) the ride of 5.85 km, powered by the electric drive (Al. Raławickie – ul. Kunickiego) – the AdBlue dosing system is off;

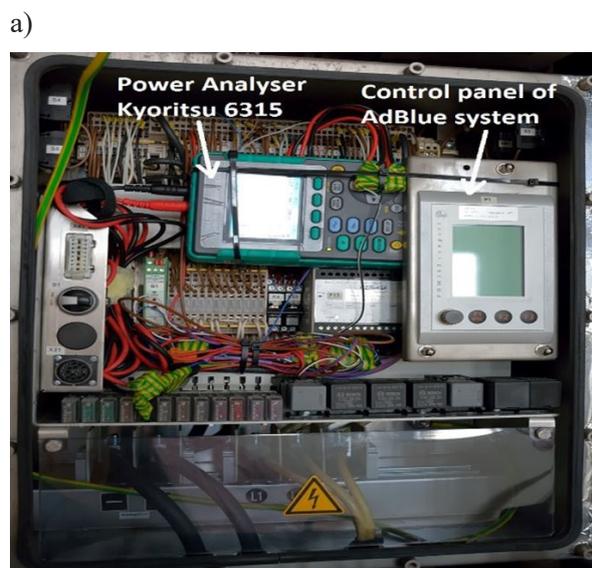


Figure 1. The front panel of the Kyoritsu analyser (a) and the place where the control box of the power consumption is located in the trolleybus (b)

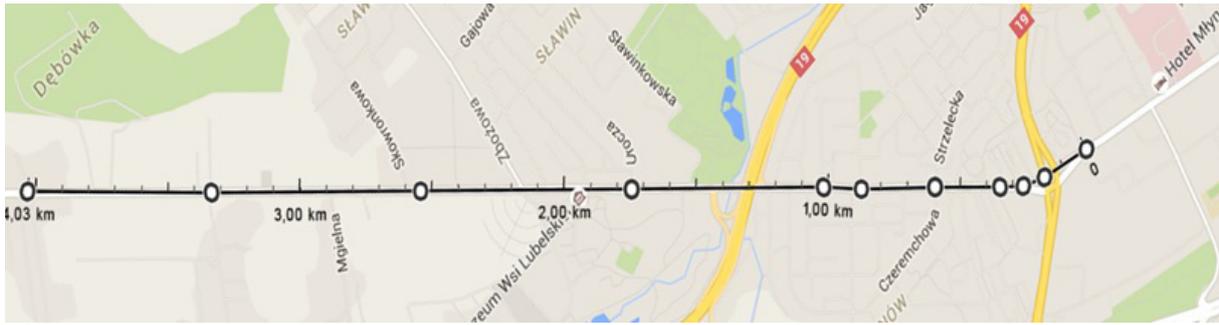


Figure 2. Part of route No. 20 in Lublin (Dębówka – Al. Raławickie)



Figure 3. Part of route No. 20 in Lublin (ul. Kunickiego – ul. Ciepłownicza)

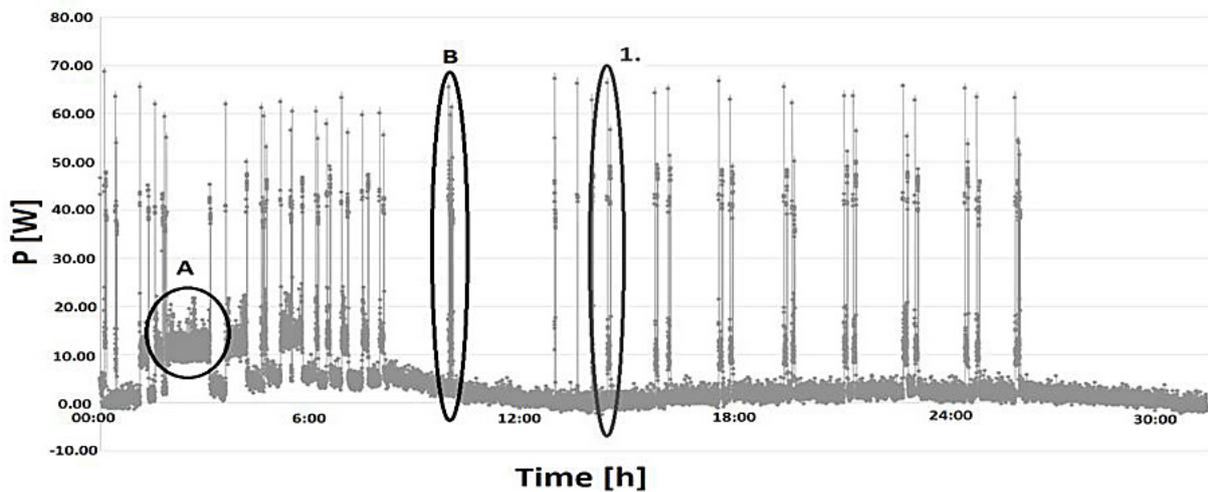


Figure 4. Instantaneous power consumption by the SCR system during the experimental ride of the Solaris 12 Trollino vehicle.

c) the ride of 2.65 km, powered by the hybrid drive (ul. Kunickiego – ul. Ciepłownicza) (Fig. 5);

The routes when the vehicle was driven with a hybrid mode are shown in the following charts:

During the first part of the route, the vehicle (Fig. 2) made 14 cycles (braking-stop-accelera-

tion). During another part of the route (Fig. 3) the vehicle made 7 cycles, on the assumption there are no traffic jams during the drive. Based on multiple rides, the daily results of the operation of the SCR system for a city transport vehicle were received.

Analysis of the first 8-hour daily cycle on route No. 160 pointed out that there are the morning peak hours (Fig. 4, point A), and the time when

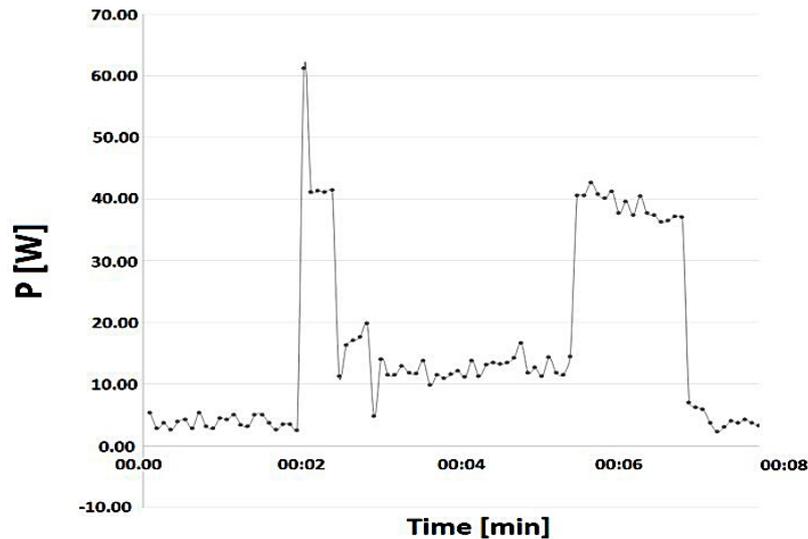


Figure 5. Instantaneous power consumption during a driving cycle of the Trollino Solaris 12 vehicle.

the vehicle came back to the depot – point B. During the morning peak hours, the vehicle was in the traffic jam, at this time it did not use full power of the system, and because of that the SCR system did not work with full efficiency. The second part (Fig. 4) shows the stable driving of the vehicle on route No. 20. For the sake of deeper analysis one driving cycle was chosen. In Figure 7 the cycle is marked with number 1.

Analysis of the one cycle of the vehicle driving pointed out that the system during the stop mode consumes power of the order of individual watts. However, when the pump starts working, the power consumption reaches the maximum value of 65 W. Then the consumption stabilises at a value which depends on the current power demand by the main drive.

Based on the statistics (Fig. 6), the SCR system consumes on average about 0.2 kWh of daily energy. The amount of energy consumed depends

on the route profile, hours during the day when the vehicle is working, and the terrain. Based on the statistical research and the assumption that the vehicle drives 300 days a year (with full load), it is possible to calculate the fuel consumption of the SCR system. To calculate all the parameters, it is necessary to make certain assumptions:

- the diesel engine efficiency is 35% and the efficiency of the vehicle’s alternator is on average 50% [14]
- Based on these data, it is possible to obtain the value of the thermal energy consumption during the day, which in this case is 1.14 kWh.

$$E_k = \frac{W_{SCR}}{\eta_{ALT} \cdot \eta_{ENG}} \quad (1)$$

where:  $W_{SCR}$  – energy collected by the system  
SCR

$\eta_{ALT}$  – efficiency of the alternator

$\eta_{ENG}$  – efficiency of the diesel engine

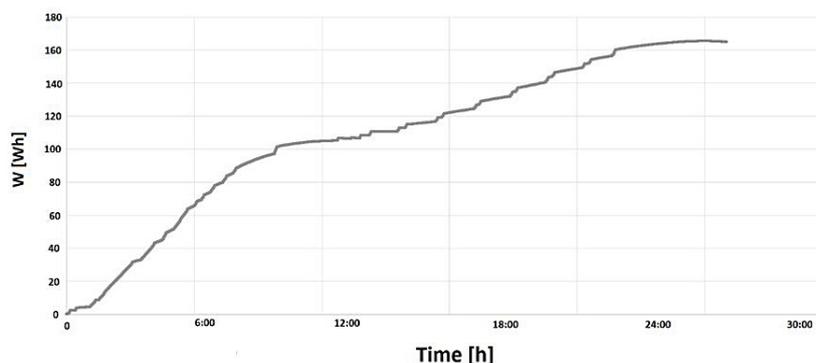


Fig. 6 Chart of the SCR system energy demand

- The obtained result, after multiplying by the number of working days, shows the value of the energy demand throughout the year, and equals 343 kWh/year.
- Based on the caloric value of the fuel, which is 36 MJ/litre (10 kWh/litre), the fuel demand for the SCR system has been calculated. In this case, it is 34.3 litres of diesel fuel per year.

## CONCLUSIONS

The paper presents the results of research on the impact of the SCR system on the operation of a vehicle with a heavy duty diesel engine. Energy consumption as a particularly important property of the working ability of the system to maintain catalytic reduction was subject to examination. In cooperation with the Lublin Municipal Transport Company (MPK), the amount of fuel for the Solaris Trollino 12 trolleybus was estimated and the energy demand found was of the order of 343 kWh/year. This gives a low diesel fuel consumption, because only 34.3 litres per year. The study also shows a graph of the daily demand of energy by the SCR system in public transport vehicles. Despite insignificant losses of diesel fuel during the year, SCR systems improve the air quality in urban areas by reducing NOx molecules harmful for humans and animals.

Future research of SCR systems in public transport vehicles is planned, using appliances recording the current terrain, the type of the road (with high and low average speed of the vehicle) and AdBlue consumption, based on the annual results.

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