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Investigation for Evaluating the Energy Recovery Capacity of the Mechanical Brake System on Urban Buses: A Case in Vietnam

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***Abstract*— Currently, traditional fossil energy is gradually exhausted for sustainable economic development, and environmental protection is an urgent requirement for all countries. Therefore, the issue of saving energy, as well as exploiting renewable energy sources, is being prioritized for development. The braking system collects dynamic energy, also known as the regenerative braking system, which is understood as the brake system; instead of converting kinetic energy into heat, the brake system can collect and store energy. The brake system of the bus in use is usually frictional. During braking, this type of brake system converts the vehicle's kinetic energy into heat, dissipates it into the surrounding environment, and cannot be recovered. Moreover, due to the operational characteristics, the bus has high stopping frequency and high braking capacity, leading to wasted energy, in addition to producing many emissions causing environmental pollution. This study focuses on experimental research for evaluating the dynamic energy acquisition of the mechanical brake system on a school bus as a function of operating parameters such as vehicle speed according to gears, vehicle mass as well as hydraulic pressure parameters. The results are noticed that the highest dynamic energy recovery rate is about 35% in the lowest gear. In the case, from the initial braking velocity of 30km/h to 0 km/h, the initial working pressure of the hydraulic tank is 100bar, the dynamic energy recovery rate is about 25%.**

***Keywords*— Regenerative braking system; dynamic energy recovery rate; renewable energy; vehicles.**

I. INTRODUCTION

Currently, traditional fossil energy sources are increasingly exhausted due to exploitation and excessive human use [1-4]. Therefore, reducing the dependence on traditional energy sources for sustainable economic development while ensuring the environmental protection task is becoming an urgent requirement for all countries [5]. The auto industry is facing two major challenges: the shortage of petrol and fuel sources [6-8] and the pressure of strict regulations on emissions and fuel consumption. Finding new solutions is an inevitable trend to reduce the above pressures [9]. One of the technological solutions attracting researchers and car manufacturers' attention is an electric vehicle, an environmentally friendly vehicle.

Among solutions to reduce the dependence on traditional fuels, the brakes' energy recovery attracts great attention of scientists. Normally, when a car brakes, its kinetic energy is converted to heat in the form of friction between the brake pads and the wheel [10]. This thermal energy can be released into the air and this is a wasteful source of energy [11][12]. Braking performance is a key factor in the safety of a vehicle. A good braking system is always required to quickly slow down the vehicle and maintain control of the vehicle's direction. The first requirement is that the brake system must provide sufficient braking torque on all wheels. Next is to distribute the brake force properly on the wheels. In general, the required braking torque is much greater than the resistance torque that an electric motor can generate (when working in generator mode), especially during emergency braking [13]. Therefore, on electric cars, hybrid cars and fuel cell vehicles (EVs, HEVs, FCVs) [14] the mechanical brake system must coexist with the regenerative electric brake [15]. So, this is a hybrid brake system. Although there are many types and methods of control in hybrid and electric vehicle engine systems, the ultimate goal of designing and controlling brake systems is to ensure braking performance and the ability to recover as much brake energy as possible [16].

On the other hand, designing a brake energy recovery system is a relatively complex issue when designing the brakes of electric, hybrid, and fuel cell vehicles [14]. There are two issues need to be addressed. Firstly, how to distribute the total brake force into regenerative brake force (the part to be recovered) and the friction brake force (the part that is not recovered) to be able to regenerate as much energy as possible; Secondly, how to distribute the total brake force on the front and rear axles to ensure braking stability and efficiency. Usually, the regenerative brake force is only effective on the active shaft. The electric motor must be controlled to produce the right amount of braking force so that the energy recovered is as large as possible, and the total braking force to slow the vehicle must be following the driver's command. To meet the above requirements, the hybrid brake system has 2 types: parallel hybrid brake system [6] and fully controlled hybrid brake system [17].

For each type of vehicle, the operating range and operating characteristics have many differences, most clearly shown in each vehicle's braking frequency and braking capacity. The relationship between the power and brake frequency of common motor vehicles is depicted in Fig.1. It can be seen that the types of buses used in urban areas, although not the greatest braking power compared to forklifts or garbage collection trucks [18]. However, this vehicle's braking frequency is very large (because the bus must continuously increase and decelerate depending on the traffic density on the road and bus stop station). In addition, the number of buses used in urban areas is very large, along with the development of public transport is an inevitable trend in the current period and tends to increase in the future [19]. Therefore, the problem of energy recovery of the brake system on urban buses brings great economic efficiency while also contributing to reducing environmental pollution [20].

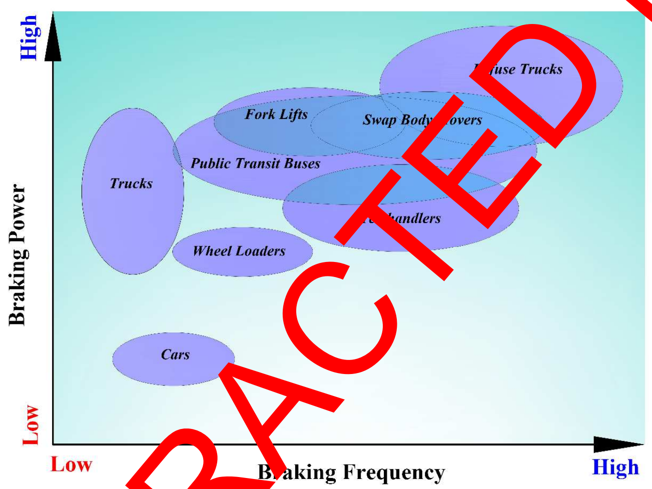

Fig. 1. Relationship between brake power and braking frequency in some vehicles [18]

In 2011, researches in Australia introduced the hydraulic brake system related system, named Hydraulic Drive Assist (HDA). These studies have been applied to some vehicle models such as garbage collection trucks, buses. With the HDA system installed on garbage collection trucks, it reduces fuel consumption by 25% [21] compared to conventional vehicles. To reflect specifically the hydraulic energy collection brake system's efficiency, we can use the parameter of cyclic energy recovery α_{ct} [22]. That coefficient is used to evaluate the efficiency of the hydraulic brake system under the test cycle. The percentage of brake energy in some vehicles is shown in Figure 2 [23]. Figure 2 shows the ratio of brake energy to the kinetic energy of some vehicle types. If the efficiency of the hydraulic drive system reaches 80%. The energy gain rate of the hydraulic brake system can be achieved in vehicles such as delivery (α_{ct} = 40%); bus (α_{ct} = 52%); refuse (α_{ct} = 47,2%) and class 8 (α_{ct} = 14,4%) [24].

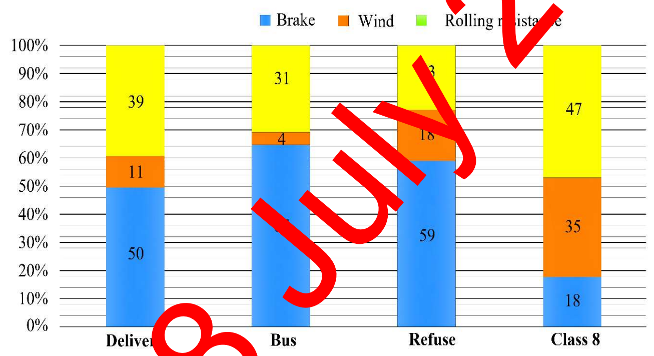

Fig. 2. The ratio of brake energy and energy losses to the total kinetic energy of selected vehicle types [23]

In Vietnam, many specialized vehicles only use friction brakes like buses in circulation [25]. Due to the operating characteristics, this vehicle must brake to pick up passengers at the stops continuously on the moving road. So this model often has a high fuel consumption, meaning many gas emissions into the surrounding environment [26]. To replace all of these vehicles with vehicles applying regenerative braking technology to reduce pollution, this is a difficult problem for the economy in developing countries like Vietnam [26]–[28]. Therefore, with the above actual situation, the study and test of hydraulic accumulator brake system model on the bus vehicle to solve the problem as follows:

- Studying the ability to collect energy with a hydraulic brake system on buses, thereby serving as the basis for developing a hydraulic energy collection system on specialized vehicles [29].
- It is used as a model for research on vehicle-related properties and hydraulic brake systems, thereby gradually approaching and mastering technology and developing hydraulic brake system products on many subjects [22].

This article presents an energy recovery plan during urban bus braking in Vietnam. The main content is focused on experimental research to evaluate the effect of the initial working pressure of the hydraulic pressure tank and the effect of the different vehicle weight and velocities at respective gears on the energy-harvesting capacity of the hydraulic brake system.

II. Materials and Method

A. Method

The experiment of measuring the basic parameters is the pressure of the hydraulic pressure tank and the vehicle speed during braking from the initial brake speed to the stop under the following cases: Change the initial working pressure of the hydraulic pressure tank; Change the vehicle velocity according to the respective gears; Change different vehicle weights.

Measured values during real-time brake kinetic energy acquisition, which serves as a basis for calculating the volume of hydraulic oil pushed into the pressure vessel V_f, energy recovered E_a, and the kinetic energy recovery ratio α by the equation (1), (2) and (3), respectively [30].

$$V_f = V_{ao}\left[\left(\frac{p_{ao}}{p_{go}}\right)^{1/k} - \left(\frac{p_{ao}}{p_g}\right)^{1/k}\right] \tag{1}$$

$$E_a = \frac{p_{go}V_{go}}{(k-1)}\left[\left(\frac{V_g}{V_{go}}\right)^{1-k} - 1\right] \tag{2}$$

$$\alpha = \frac{E_a}{\Delta E_v}100\% \tag{3}$$

Where:

V_{ao} - initial gas volume according to tank capacity (m^3);

p_{ao} - initial intake pressure of the accumulator (N / m^2);

p_{go}- initial working pressure of the accumulator, the minimum working pressure (N/m^2);

p_g- working pressure of the accumulator (N/m^2);

k - adiabatic exponent, choose to use nitrogen k = 1.4;

V_{go} - the initial working volume of the gas corresponding to the p_{go} [m^3];

V_g- the volume of the compressed gas corresponds to p_g [m^3];

ΔEv- the variation of vehicle kinetic energy at the initial braking velocity v_0 to v_t;

The principle diagram of the proposed hydraulic regenerative brake system (HRBS) is shown in Fig.3. there: 1- oil tank; 2 - pump; 3- control valve; 4-return line; 5-check valve; 6- pressure transducer; 7 - pressure switch; 8 – hydraulic-electric accumulator; 9- reusable oil; 10 - pressure indicator; 11- Power take-off; 12- proximity sensor (electromagnetic); Br – signal from pedal; Pacc - signal from transducer; V1 - valve control signal; CL-control signal of Clutch take-off; CLPTO-PTO-on-control signal [31].

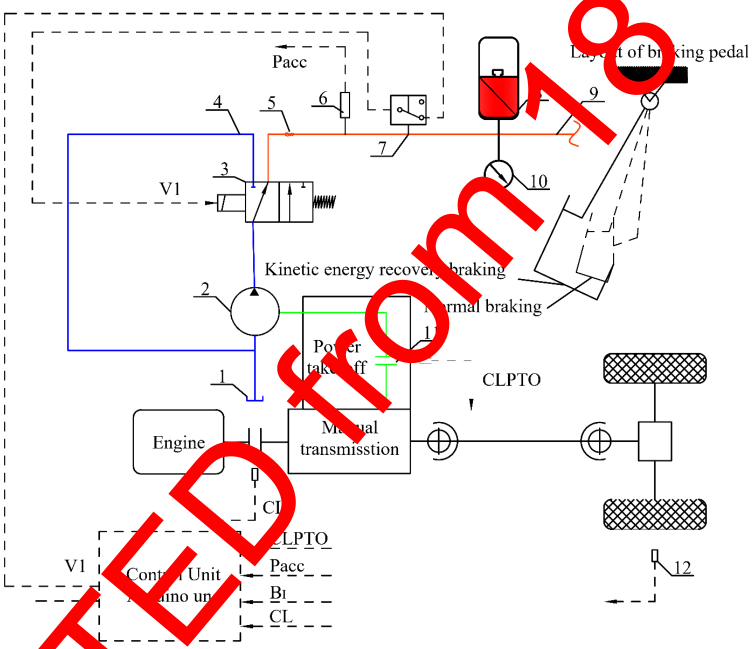

Fig.3. The principle diagram of the hydraulic regenerative brake system

TABLE I
THE BASIC PARAMETERS OF THE ARDUINO UNO R3 CARD [32]

Specifications	Value
Microcontrollers	ATmega328 with 8bit
Operating voltage	5V DC (supplied via USB port only)
Operating frequency	16 MHz
Current	30mA
Recommended input voltage	7-12V DC
Limit input voltage	6-20V DC
The number of Digital I / O pole	16 (6 pins hardware PWM)
The number of Analog pole (A0, A1, A2, A3, A4, A5)	6 (10bit resolution)
Maximum current per I / O pole	30 mA
Maximum output current (5V)	500 mA
Maximum output current (3.3V)	50 mA
Flash memory	32 KB (ATmega328)
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)

B. Materials

Hydraulic pump: Gear type hydraulic pump; Specific flow rate: dp = 14 cc/round; Maximum speed: 2500 rpm. Control valve: Maximum flow rate: 63 liters/min; Maximum working pressure: 31.5Mpa. Hydraulic pressure tank: Volume: V_{ao} = 25 liters; Maximum working pressure: 31.5MPa; Working temperature: -19°C ÷ 70°C. Pressure sensor: Working temperature: -40°C ÷ 100°C; Maximum working pressure: 250bar; Supply voltage (2 poles) DC:8÷28 V; Signal output current: I_{out} = 4÷20mA; Accuracy: ± 0.5FS.

Proximity sensor: Operating voltage: DC: 6 ÷ 36V; Farthest detecting distance: 8 mm; Operating temperature: -25°C ÷ 55°C. To control the system's operation during braking, the controller has been designed on the Proteus program, the controller uses an open-source Arduino Uno R3 card loaded with program code. Arduino Uno R3 card has the same basic parameters as in Table I, the control signal from Arduino Uno R3 card has a maximum voltage of 5V, so to control the hydraulic solenoid valve operation with a voltage of 24V [32].

TABLE II
THE EXPERIMENTAL PLANNING PARAMETERS OF 3 EXPERIMENTAL

Specification	Experiment No.1			Experiment No.2				Experiment No.3	
Initial working pressure, p_{go} [bar]	75	85	95	85	85	85	85	85	85
Vehicle weight, m [kg]	2400	2400	2400	2400	2400	2400	2400	2400	1800
The number of gear position	3	3	3	1	2	3	4	3	3
Initial vehicle velocity of braking process, v_o[km/h]	30	30	30	7.5	15	30	50	30	30

C. Experimental setup

Table II summarizes the experimental planning parameters of the tests conducted in this study. Experiment No.1: Experimenting on the effect of initial working pressure on the braking system's dynamic energy recovery process. Vehicle weight is 2400kg; Initial vehicle velocity of braking process is 30km/h; Gear is No.3; Change the initial working pressure of the accumulator: p_{go} = 75bar, 85bar and 95bar, respectively.

Experiment No.2: Experimenting with the ability to recover the brake's energy according to the different braking initial velocities is applied to the corresponding gear. Vehicle weight is 2400kg; Initial vehicle velocity of braking process is 7.5km/h, 15km/h, 30km/h and 50km/h at the respective gear of No.1, No.2, No.3 and No.4, respectively; The initial working pressure of the accumulator is 85bar. Experiment No.3: Experimenting with the ability to recover the brake's energy according to the different weights of vehicle. Vehicle weight is 2400kg and 1800kg; The braking process's initial vehicle velocity is 30km/h at the gear of No.3; The initial working pressure of the accumulator is 85bar.

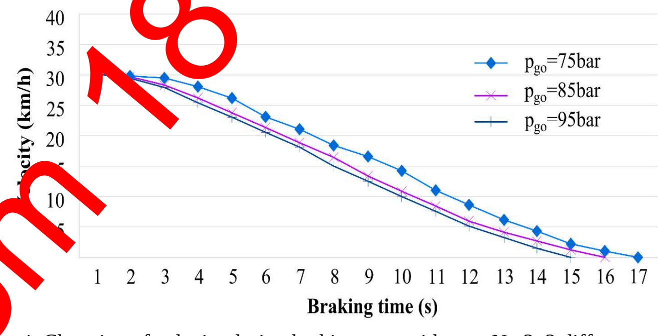

Fig. 4. Changing of velocity during braking runs with gear No.3, 3 different p_{go} modes

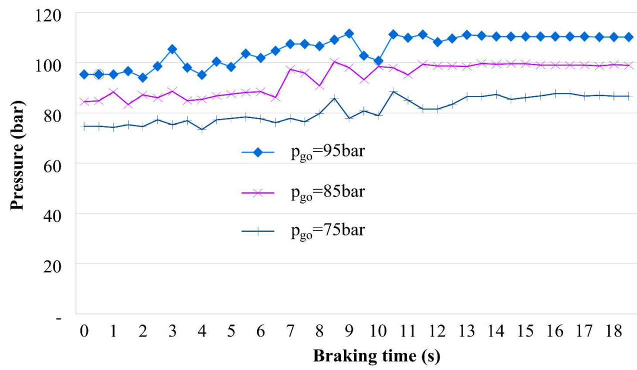

Fig. 5. Changing of pressure in the accumulator during braking to recover energy with v_o = 30km/h, gear No.3, 3 different p_{go} modes

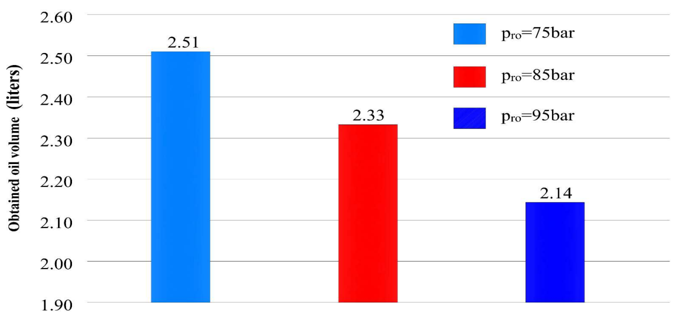

Fig. 6. Changing of obtained oil volume during braking to recover energy with v_o = 30km/h, gear No.3, 3 different p_{go} modes

III. RESULTS AND DISCUSSION

A. Effect of Initial Working Pressure on Brake Kinetic Energy Recovery

The results of measurement of brake time and acceleration are obtained in 3 cases: at p_{go} = 75bar, braking time is 16s, average braking acceleration is 0.52m/s^2; at p_{go} = 85bar, braking time is 15s; average braking acceleration is 0.56m/s^2; p_{go} = 95bar, braking time is 14s, average braking acceleration is 0.60m/s^2. Therefore, the p_{go} setting value has a clear impact on the dynamic braking parameters. Specifically, when the accumulator's initial working pressure increases, the braking time decreases while the average braking acceleration increases.

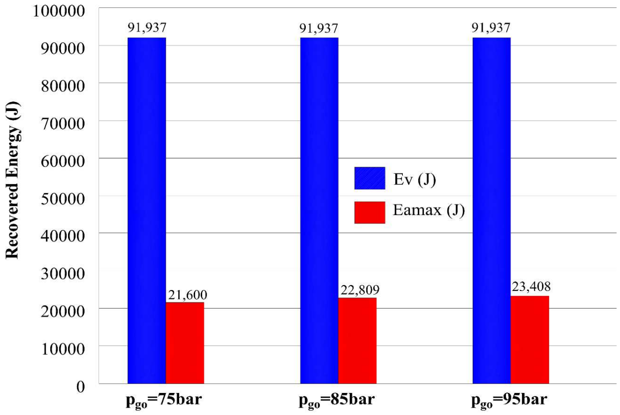

Fig. 7. The ratio of energy recovery during braking to recover energy with v_o = 30km/h, gear No.3, 3 different p_{go} modes

During braking at an initial velocity of 30km/h, the variable dynamic energy is 91937J for 3 cases. Experimental data synthesizing from Fig. 4, Fig. 5, Fig. 6 and Fig. 7 showed that the brake system's energy recovery rate increases from 23.49% to 25.46% when the initial working pressure changes from 75bar to 95bar. Case 1: p_{go} = 75bar, the maximum obtained pressure is 88bar, obtained hydraulic oil volume is 2.51 liter, recovered energy is 21600J with the rate of 23.49 %. Case 2: p_{go} = 85bar, the maximum obtained pressure is 99.63bar, obtained hydraulic oil volume is 2.33 liter, recovered energy is 22809J with the rate of 24.81 %. Case 3: p_{go} = 95bar, the maximum obtained pressure is 111.26bar, obtained hydraulic oil volume is 2.14liter, recovered energy is 23408J with the rate of 25.46%.

B. Effect of Initial Velocity on Brake Kinetic Energy Recovery

The synthetic results in experiment No.2 are shown in Fig.8, Fig.9, Fig.10 and Fig.11 that are given the brake system model's energy recovery capacity at different initial braking velocities. Case 1: the bus works with gear No.1, v_o = 7.5km/h, dynamic energy of 5746J, braking time of 2s, average brake acceleration of 1.0m/s^2, accumulated hydraulic oil volume of 0.00023m^3, working pressure reached to 86.3bar, obtained energy of 1982J, and α = 34.5%. Case 2: the bus operates at gear No.2, v_o = 15km/h, dynamic energy of 22984J, braking time of 6s, average brake acceleration of 0.64m/s^2, accumulated hydraulic oil volume of 0.00083m^3, the working pressure of 89.75bar, obtained energy of 7298J, and α = 31.75%. Case 3: the bus operates at gear No.3, v_o = 30km/h, dynamic energy of 91937J, braking time of 13s, average brake acceleration of 0.64m/s^2, accumulated hydraulic oil volume of 0.00233m^3, the working pressure of 99.63bar, obtained energy of 22809J, and α = 24.81%. Case 4: the bus operates at gear No.4, v_o = 50km/h, dynamic energy of 255380J, braking time of 35s, average brake acceleration of 0.4m/s^2, accumulated hydraulic oil volume of 0.00517m^3, the working pressure of 124.22bar, obtained energy of 62957J, and α = 24.65%.

Fig.11 clearly shows that when the initial velocity increases, the better the ability to recover the braking process's energy. However, in terms of efficiency, in case 1 corresponding to gear No.1 and v_o is the smallest, the energy recovery ratio is highest.

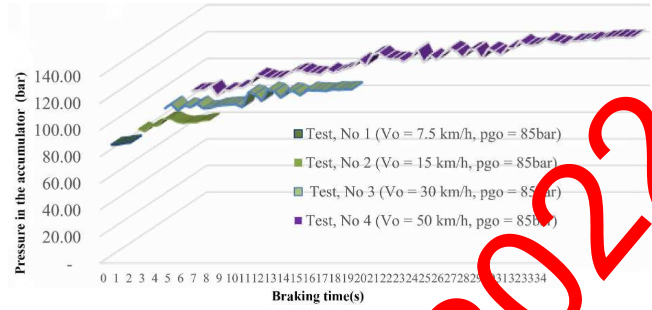

Fig. 8. Changing of pressure in the accumulator during braking energy recovery process at different initial velocities (v_o) and p_{go} = 85bar

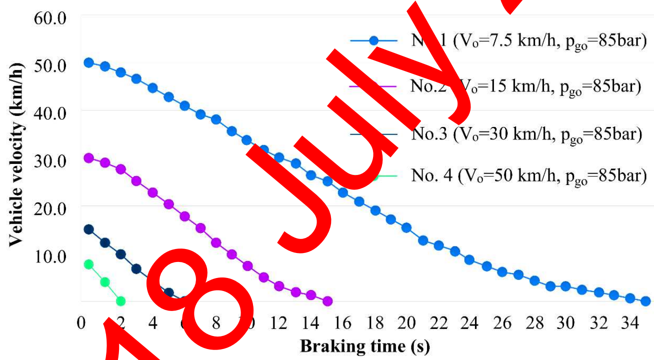

Fig. 9. Changing of vehicle velocity (v_t) during braking energy recovery process at different initial velocities (vo) and p_{go} = 85bar

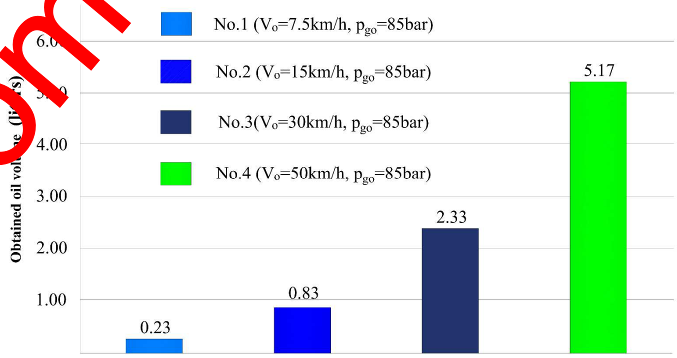

Fig. 10. Changing of obtained oil volume during braking energy recovery process at different initial velocities (v_o) and p_{go} = 85bar

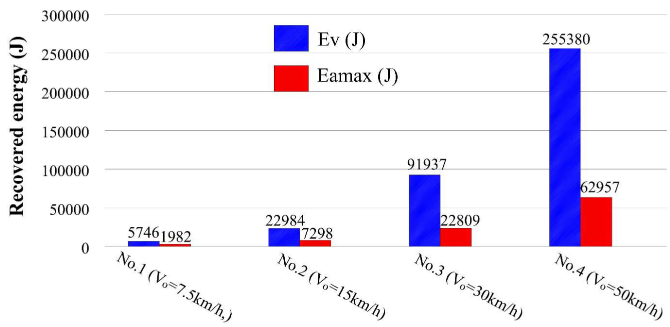

Fig. 11. The ratio of energy recovery during braking energy recovery process at different initial velocities (v_o) and p_{go} = 85bar

C. Effect of Vehicle Weight on Brake Kinetic Energy Recovery

With test No. 3, initial velocity 30km/h, gear No.3, changing vehicle weight in different cases, experimental results are shown in Fig.12, Fig.13, Fig.14 and Fig.15. With vehicle weight of 1800kg, it takes 13s for the bus braking from v_o = 30km/h to stop, dynamic energy of 71103J, braking time of 13s, average acceleration of 0.64m/s^2, accumulated hydraulic oil volume of 2 liters. Meanwhile, the working pressure in the accumulator increased from 85bar to 97.3bar, the obtained energy was 19120J, reaching the ratio α = 26.89%.

In another case, a 600kg increase in vehicle mass, while a braking velocity kept at 30km/h resulted in an increase in kinetic energy by 20834J and braking time reach to 15s. Furthermore, the average acceleration has a drop to 0.56m/s^2, the working pressure extends the range from 85bar to 99.63bar, accumulated hydraulic oil volume of 2.33liters, the recovered energy is 22809J, the energy recovery ratio is reduced to 24.81%.

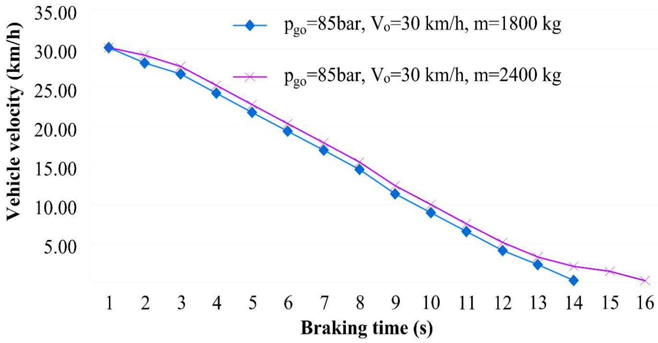

Fig. 12. Changing of vehicle velocity (v_t) during braking energy recovery process at different vehicle weights, v_o=30km/h and p_{go} = 85bar

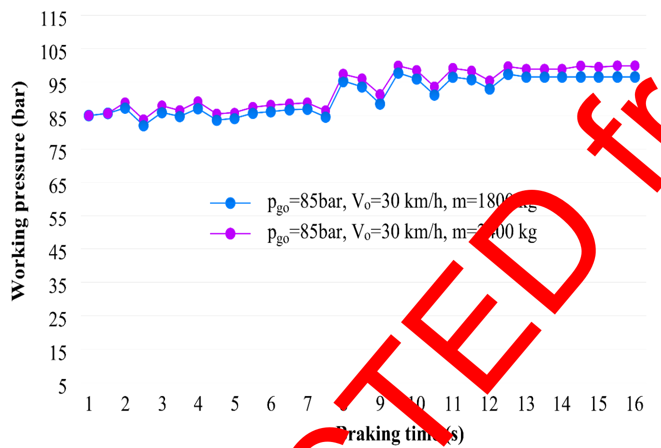

Fig. 13. Changing of working pressure during braking energy recovery process at different vehicle weights, v_o=30km/h and p_{go} = 85bar

Fig. 14. Changing of obtained oil volume during braking energy recovery process at different vehicle weights, v_o=30km/h and p_{go} = 85bar

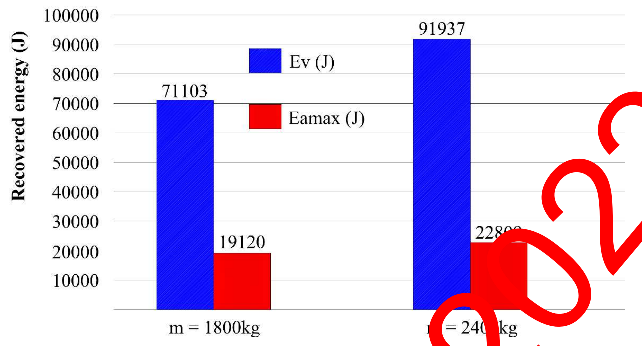

Fig.15. The ratio of energy recovery during braking energy recovery process at different vehicle weights, v_o=30km/h and p_{go} = 85bar

VI. Conclusion

The paper has conducted an experimental study on the school bus brake system to evaluate the effect of the initial working pressure of the accumulator as well as the influence of vehicle weight and braking velocity on the energy-harvesting capacity of the hydraulic system that recovers mechanical brake energy. Experimental results have shown the energy recovery capacity of the experimental system models, as follows: rate of braking energy recovery is the highest at the lowest gear, and gradually decreasing in high gear. In gear No.1and initial velocity of 7.5km/h, the energy-harvesting system has achieved α = 34.5%. However, in gear No.2, v_o=15km/h, braking energy recovery rate reduced to 31.75%. Also, with input parameter set of (gear No.3, 30km/h) and (gear No.4, 50km/h), it is recorded that reduction of α is 24.81% and 24.65%, respectively. In an accumulator, the initial pressure tends to be proportional to the higher rate of brake energy recovery (p_{go} = 75 bar, α = 23.49%; p_{go} = 85 bar, α = 24.81%; p_{go} = 95 bar, α = 25.46%). The increase in vehicle weight is not conducive to brake energy recovery efficiency. Thus, this study has demonstrated that the recovery of energy during the braking process of buses used in urban areas can help save fuel, bring high economic efficiency, and reduce environmental pollution.

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