STRATEGY TO REDUCE POLLUTION FROM SERBIAN PUSHBOATS

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Abstract: Moving a cargo by ships from one point to another point is a fuel efficient method and certainly presents the lowest pollutant emission mode of transport of all transport systems if we consider long distance movement per tonne basis. Diesel engines are already efficient and while highly efficient, ships are not an insignificant source of carbon emissions at a global level. A strategy for overall decrease in pollution from ships through fuel consumption was presented in this paper. Combining ship hull form characteristics and propulsion plant parameters it has been shown that there are more options for reducing the carbon impacts of ships through lower fuel consumption. The study is based on self-assessment of hull powering performance using propulsion shaft torque data from torsion meters installed on ships and ship speed data obtained from experimental measurement. Periodic speed/power measurement could enable ship's crew to forecast an appropriate time for hull maintenance in order to achieve the minimizing of fuel consumption, as well as reducing pollution from ships. The concept of speed measurement for assessing power performance is not a new concept. The results for Serbian pushboats were presented. The results showed that this procedure could be applied over time during the operating life of a ship.

Keywords: component, fuel consumption, full-scale measurement, transport efficiency, fuel efficiency, ship powering.

1. Introduction

The price of pollution is increasing with new and increased industrialization. Today, sources of power or engines in automobiles, trucks, aircraft and ships are examples of how modern world is breathing from day to day and from hour to hour, but on the other side, engines generate atmospheric chemicals. Pollution from transportation means degrades the quality of life by decreasing visibility, damaging infrastructure, natural world and society's health.

Inland waterway transportation, the oldest of all transport modes, largely depends on environmental conditions such as the depth and width of a waterway, streams and their velocity, variations of water levels, maintenance and equipment of navigational aids, level of the use of information and management systems, port equipment and capabilities, as well as market conditions. Inland navigation is very competitive in relation to the other inland transport modes. Pushed convoy or just convoy (composed of pusher and pushed barges) can generate more distance movement per tonne basis than any other surface transport mode (Radmilović and Maraš, 2011).

According to the data of the Economic Commission for Europe, the Committee for Inland Transport of the United Nations

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operating from Geneva, the Commission of the Transportation Ministries of the European Community Member Countries, various national associations and scientific organizations in European countries, inland waterway transportation is characterized by the lowest propulsion energy consumption and is environmentally the friendliest type of cargo transportation.

Diesel main propulsion engines are used for main propulsion for almost all ships in Serbian fleet including pushboats, self-propelled vessels and many large and small auxiliary ships. Although economic pressures forced conversion to more efficient diesel powering, they also caused increasing levels of pollutant emissions from ships such as nitrogen oxides (NO_x) and sulphur oxides (SO_x).

The vast majority of pushboats are equipped with two main diesel engines although a small number of pushboats have three main diesel engines. Installed power on Serbian pushboats ranges from 200 kilowatts to 2500 kilowatts. By comparing pushboats with tugs it becomes obvious that pushboats are smaller with lower length and with two propellers turning outwards and working in the zone of the flow field. In this way it is possible to achieve a higher ratio of the effective power to the thrust or the so-called hull efficiency.

Today, there is no specified procedure adopted by the authorities or shipping companies to test fuel consumption during the operation with a fleet. Developing the ship's operating profile (pushboat engine power and shaft RPM) involves determining the time of operation at a specific speed and power combination (Markle and Brown, 1996). The operating profile developed in this paper considered steady state operation only achieved in full-scale measurement.

Hull form shape and wetted surface area determine the ship's powering requirement for a given speed. Commercial pushboat engines are designed to provide optimum fuel economy at some convoy speed. For an established speed, the shaft RPM and engine power are relatively constant. For most of pushboats' operational life their convoy speeds range from 8 to 14 kilometers per hour.

Like all commercial vessels, Serbian pushboats are also getting underway for profit and are typically operated at speed and power combinations that maximize fuel efficiency (Markle and Brown, 1996). Unlike seagoing vessels, river ships do not tend to follow tracks that minimize the distance between ports.

The goal of this paper is to provide a brief review of ship powering and full-scale measurements; to discuss the relationship of speed vs. power and to compare fuel consumption between two different convoys with two different tests.

Two pushboats and their convoys have been selected for study. Among the number of conducted measurement procedures two tests were considered in a span of 7 years. The reason why these tests were used is because both pushboats had the same installed power and the same formation of barges utilized in the measurement.

The results show fuel efficiency variation according to shaft power in kilowatts. Convoy speed appears as the most important value for determining the travel time. It is revealed that the barge formation with bigger operating displacement has lower fuel consumption per shaft power. By adding more engine power fuel consumption as well as convoy speed is expected to increase while travel time should be shortened.

2. Ship Powering Tests

Ship propulsion plant provides sufficient power to overcome ships' resistance. This resistance is composed of two main components: frictional resistance and residuary resistance. Although frictional resistance is the larger part of the two resistance components, it is proved by resistance and self-propulsion tests that residuary resistance can contribute in more than 50 % of total resistance. Frictional resistance accounts for 80 to 85 % of total resistance in slow-speed ships, while in high-speed ships it can reach up to 50 % of total resistance (Lewis, 1988). Environmental effects, such as wind, waves and currents do not contribute to frictional resistance on river ships.

Residuary resistance contains wave resistance and form (viscous) drag. Residual resistance is usually expressed as a function of the Froude number but largely depends on the ship's type and dimensions. It is well known that pusher-barge systems with the same number of barges but arranged in a row (shorter length overall but with a larger breadth) and with the higher draft overall require more power to operate than those that were arranged in a line (King et al.,. 2008). Two pusher-barge systems with the same wetted surface area, but differing in length and breadth (barges are differently arranged) will have different resistance and greater or lesser proportion of residual resistance in total resistance.

The proper determination of ship power gives the organizers of the transport process the possibility of creating effective solutions in a number of important production tasks. Predicted or calculated ship resistance allows the selection of the best ship speed versus ship power, proper selection of a pushed convoy on the river, accurate calculation of transportation costs and also the benefits of decreasing pollution from ships.

For predicting ship powering requirements naval architects can use scale model testing or ship powering tests to analyze each installed system under actual operating conditions. Ship powering includes various tests regarding self propulsion and resistance taking the dimensions of displacement hulls, barges etc. both in deep and shallow water, helping to track out the full scale powering performance and speed. It often happens that it is not possible to do the ship model testing or full-scale measurement, and the only way to determine ship resistance and ship power is by applying various empirical equations. If ship power is changed over time, it is often necessary to conduct more full-scale measurement procedures during the life of a ship.

Today, an accurate determination of the speed/power relationship for commercial pushboats is normally performed. This hull powering performance assessment is accomplished through standard full-scale measurement procedures which occur during the post-commissioning test, trial period and during the ship's service life when it is necessary to discover a new relationship between speed and power. For this paper full-scale measurement procedures were used during the ship's service life, or after some period of time of the ship's operation.

Two full-scale measurements were conducted and all the data are collected in Table 1. Two Serbian pushboats took part in the full-scale measurement procedures with installed power of 2·515 = 1030 HP. According to (Čolić, 2006) the following measurement procedures were followed:

1. Propeller shaft horsepower (SHP) or ship shaft power,

2. Rotation rate or shaft RPM,
3. Ship speed (v) in relation with propeller shaft horsepower and shaft RPM,
4. Fuel consumption on two main engines with various operating modes.

The main dimensions of pushboats "Panonija" and "Pinki" are:

Length overall: 31.27 m; Extreme beam: 9.55 m; Design draft: 1.80 m; Design Displacement: 338.75 t; Freeboard: 0.78 m; Depth: 2.55 m

Only symmetric barges were used when composing the pushed convoy. The main characteristics of symmetric barges were:

Length overall: about 71.00 m; Extreme beam: about 11.60 m; Design draft: 2.50 m; Operating displacement (Q): 1500~1561 t

The full-scale measurement procedures were carried out for the following formations of barges:

1. 2-barge pushed convoy with one leading barge in front of the convoy and one barge in the mid section of the convoy (notation "1+1")
2. 2-barge pushed convoy with two leading barges (notation "2+0")
3. 3-barge pushed convoy with one barge in front of the push string, one barge in the mid section of the push string and one barge directly ahead of the pushboat (one by one barges in formation – notation "1+1+1")
4. 3-barge pushed convoy with one leading barge in front of the convoy and two barges in the mid section of the convoy (one by two barges in formation – notation "1+2")
5. 4-barge pushed convoy with two leading barges in front of the convoy and two barges in the mid section of the convoy (two by two barges in formation – notation "2+2")
6. 3-barge pushed convoy with three leading barges (notation "3+0")

The measurement of power and speed in both propeller shafts was performed with torsion meters. Transmitting and receiving elements of torsion meter were placed in the stern of the ship and thus protected from the influence of the engine room. Forces directly measured at the propeller shafts were slightly lower in values than the actual force that was developed by the engine, because there were some losses in the bearings, buckles and gearboxes. For more accurate calculations these losses have to be taken into account and they are approximately about 2.5 % to 3.0 %. These losses are expressed in the shafting efficiency η_S. Eq. (1) provides this relation for the pushboats:

$$ç_S = \frac{SHP}{BHP} = 0.97 \tag{1}$$

Convoy speed through water was determined by a hydrometric wing, which was set to the side of the leading barge(s) but closer to the bow of the convoy. During the measurement the hydrometric wing was submerged to a depth of approximately 0.8 meters while it was away from the leading barges about 3.5 meters at the same time. Thus it can be considered that the hydrometric wing was operated in relatively undisturbed water.

Convoy speed is varied by shaft RPM, and propellers pitch was not taken into consideration since it is set at 100 %. Operating displacement is a factor that in normal circumstances can affect the speed, but is actually insignificant as the barges are maximally loaded and will always be in real operation. Fig. 1 gives the relation between shaft RPM and convoy speed for the "1+2" formation of barges and Fig. 2 for the "2+2" formation of barges.

The convoy speed from Fig. 1 and Fig. 2 is modelled linearly dependent on shaft RPM. Two curves of Fig. 1 and Fig. 2 are represented by Eqs. (2) and (3):

$$v = 0.0487 \cdot RPM - 0.2899 \qquad (2)$$

$$v = 0.0521 \cdot RPM - 2.6341 \qquad (3)$$

During the tests, fuel consumption was measured at the main propulsion engines for maximum allowed charging and continuous operation.

All full-scale measurement procedures were used on the Danube, in the test area between km 1100 and km 1122 and at different period of time which had impacts on the water levels. It was possible to plot the hydrological data such as the depth of the water, width of the navigable area and average speed of the current in the test area as a function of the water level.

Test conditions were well defined and the results for the relation between speed and power are presented in Table 1, Fig. 3 and Fig. 4. The measured data were divided by formations of the barges in Table 1 as well as in Fig. 3 and Fig. 4. Only two types of formation are considered: "2+2" and "1+2". Although in Table 1 the data are divided according to pushboats, in Fig.3 and Fig. 4 the same data are classified by barge formations.

Operating displacement, speed and power, from Table 1 were treated as first order variables. The data from Table 1 provides the relation between speed and power. The curve fitting the measured speed and shaft power data provides the speed vs. power graph given in Fig. 3 ("2+2" formation) and Fig. 4 ("1+2" formation). The curve of Fig. 3 is represented by Eq. (4) while Fig. 2 is represented by Eq. (5).

$$SHP = 14.038v^2 - 126.11v + 517.95 \qquad (4)$$

$$SHP = 5.6511v^2 + 24.598v - 356.66 \qquad (5)$$

Correlation coefficient is higher than 0.91 but lower than 0.94 in both cases (formations) for shaft RPM and shaft horse power (SHP) which explains the difference of 7 years between the two full-scale measurement procedures.

3. Pushboat Operating Profile

Commercial ships operate for profit and typically at speed and power combinations that maximize fuel efficiency. Inland waterway ships do not tend to follow tracks that minimize the distance between two ports. It does not mean that those vessels are not concerned with fuel economy. Efficiency is usually reached with different vessel speeds because other operational requirements do not require that much fuel consumption. For example, if the ship is in port, shore services are connected and ship is getting electrical power and fresh water from the port. Although main diesel engines have to be started several hours before the ship is to leave the port, it is obvious that the time needed for navigating to the next port is greater than the time needed for leaving the port.

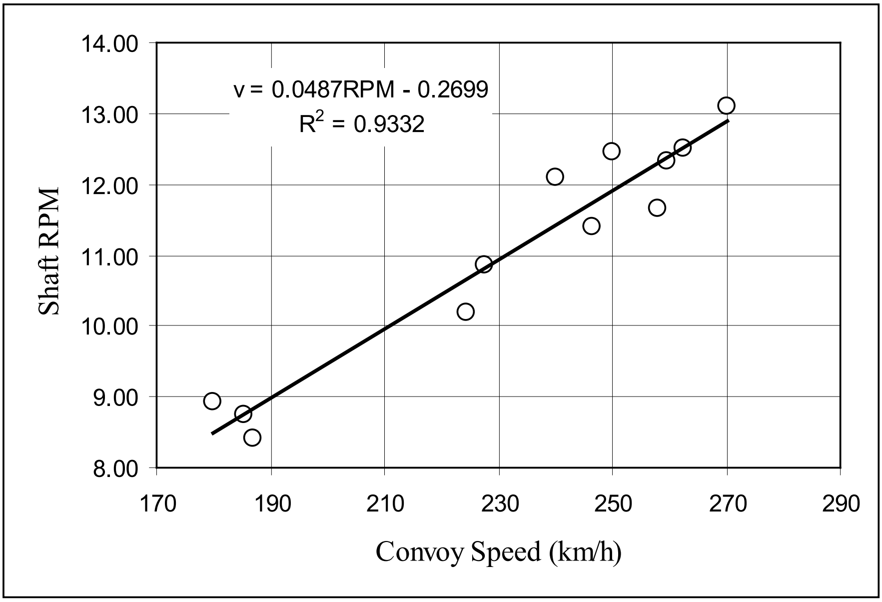

Fig. 1.
Convoy Speed vs. RPM for "1+2" Formation

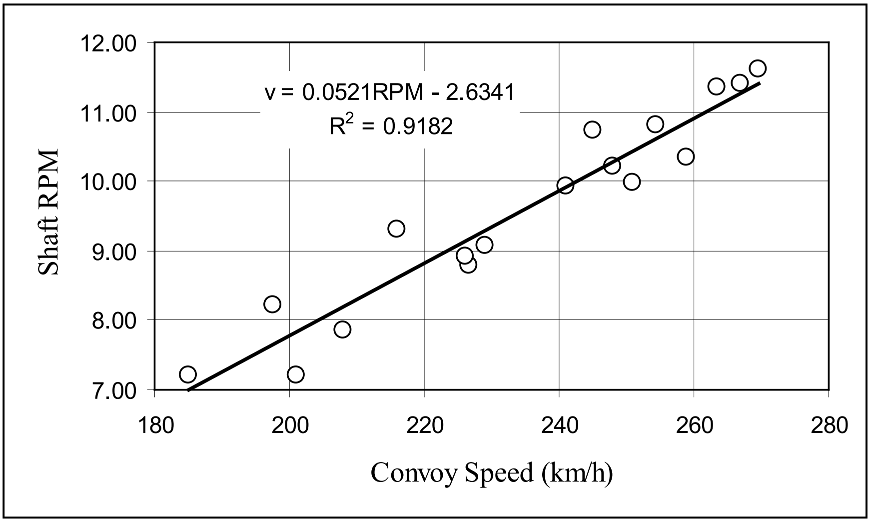

Fig. 2.
Convoy Speed vs. RPM for "2+2" Formation

Table 1 *Database from full-scale measurement procedures*

Formation of barges		Total shaft power (horsepower and kilowatt)		Rotation rate or shaft RPM	Speed (kilometers per hour)	Operating displacement (tonnes)
"Pinki"						
1 + 2	First test	977.2	719.2	270.0	13.1	4453
		898.9	661.6	262.5	12.5	
		791.4	553.0	246.5	11.4	
1 + 2	Second test (after 7 years)	721.0	530.3	250.0	12.445	4395
		676.2	497.3	240.0	12.107	
		294.3	216.4	180.0	8.935	
2 + 2	First test	980.0	721.3	269.5	11.6	5930
		952.0	700.7	267.0	11.4	
		754.7	555.5	248.0	10.2	
		570.2	419.7	226.6	8.8	
		396.3	291.7	201.0	7.2	
2 + 2	Second test (after 7 years)	727.0	534.7	246.5	10.829	5861
		745.9	548.6	246.5	10.919	
		701.9	516.2	245.0	10.742	
		472.4	347.5	216.0	9.313	
		330.3	243.0	197.5	8.213	
"Panonija"						
2+2	First test	890.0	655.0	263.5	11.35	5894
		791.7	582.7	254.5	10.80	
		660.1	485.8	241.0	9.93	
		542.2	399.1	226.0	8.92	
		428.4	315.3	208.0	7.85	
2+2	Second test (after 7 years)	783.8	576.4	259	10.33	5917
		704.5	518.1	251	9.97	
		526.2	387.0	229	9.08	
		281.6	207.1	185	7.20	
1+2	Second test (after 7 years)	760.0	558.5	258	11.65	4382
		488.4	359.2	224.5	10.20	
		276.6	203.4	187	8.42	
1+2	Second test (after 7 years)	772.3	568.1	259.5	12.32	4382
		508.0	373.6	227.5	10.87	
		275.4	202.5	185.5	8.75	

A typical operating profile for pushboats "Pinki" and "Panonija" is characterized by operation at specific speeds and power combinations. Since operating profile covers multi-functional tasks, a study on each operating mode will help in calculating fuel consumption. Fig. 5 provides a flowchart usually needed for the calculation of engine brake horse power (BHP) and shaft RPM using Eqs (1) through (5) presented in the previous section. The method illustrated in Fig. 5 links ship speed to ship power. Data for the ship's operating profile are collected through the full scale measurement presented in the previous section.

4. Analysis of Fuel Consumption Data

Testing of fuel consumption has been done for the both of formations "2+2" and "1+2". Measured fuel consumption (G) of both engines and calculated specific fuel consumption (G_S) for both pushboats are shown in Table 2. Brake power is calculated based on the losses in the shafting plus additional mechanical efficiency. Power losses between engine and total shaft power are typically 3 % for Serbian pushboats.

As can be seen from Table 2, fuel consumption rate depends on the engine's output: the more power, the higher fuel consumption. However, the final consumption rate depends on the main engine output and working rate (Anastassios and Athanasios, 2008) which could be proved with the shaft RPM data from the full-scale measurement procedures.

5. Results from Data Analysis

Transport efficiency (E_t) or transportation efficiency is one of the most important technical and operating measures by which the cost of transport can be reduced and fleet made more competitive. With this coefficient it is not only the power required that is taken into account, but also the operating displacement of the ship and the time required to move that weight (the speed of the ship). It is defined as tonnes-kilometers per kilowatt-hour, Eq. (6):

$$E_t = Q \cdot v / SHP \tag{6}$$

Fuel efficiency (F_E) is expressed in terms of consumption per ship distance per mass of cargo transported (operating displacement), Eq. (7):

$$F_E = G_S / E_t \tag{7}$$

The method presented in this paper provides an accurate way of calculating the range of speed and power points at which engine is operated, and also easy to use.

Table 3 provides data comparison between two mentioned barge formations. Fig. 6 illustrates the comparison graphically.

The comparison charts of Fig. 3 show fuel efficiency variation according to shaft power in kilowatts. What is not presented in Fig. 3 is the speed of the convoy. But convoy speed is the most important value for determining travel time. Comparing the formations "1+2" and "2+2" in Fig. 3 it is revealed that the formation "2+2" has lower fuel consumption per shaft power which is expected if operating displacement is taken into account. By increasing engine power fuel consumption and convoy speed are expected to increase and travel time to become shorter. Depending on the time of arrival at the destination port, convoy speed will be determined. On the basis of determined convoy speed and by using Eqs (1) and (2) pushboat power is calculated, which in overall results in fuel consumption savings.

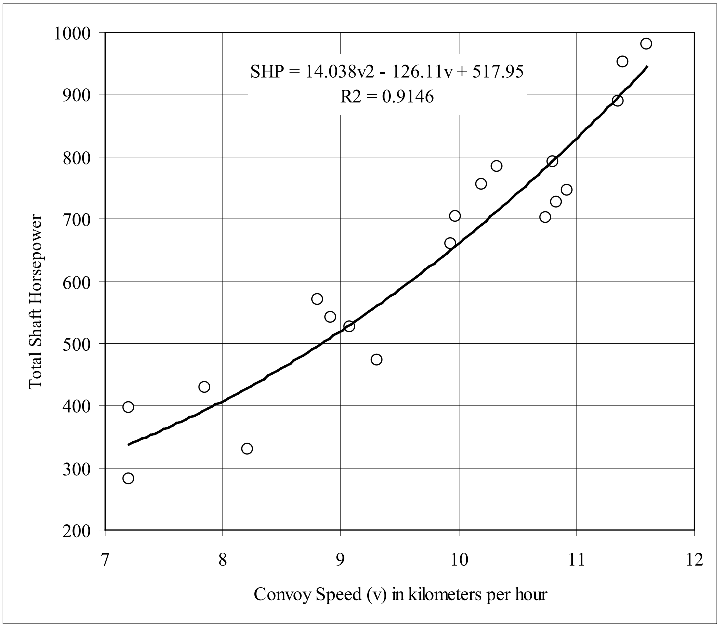

Fig. 3.
Speed/ Power Curve for "2+2" Formation

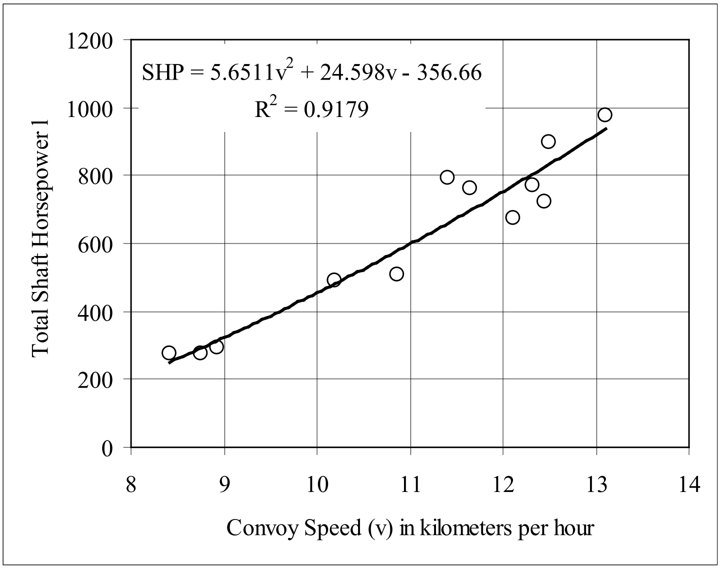

Fig. 4.
Speed/ Power Curve for "1+2" Formation

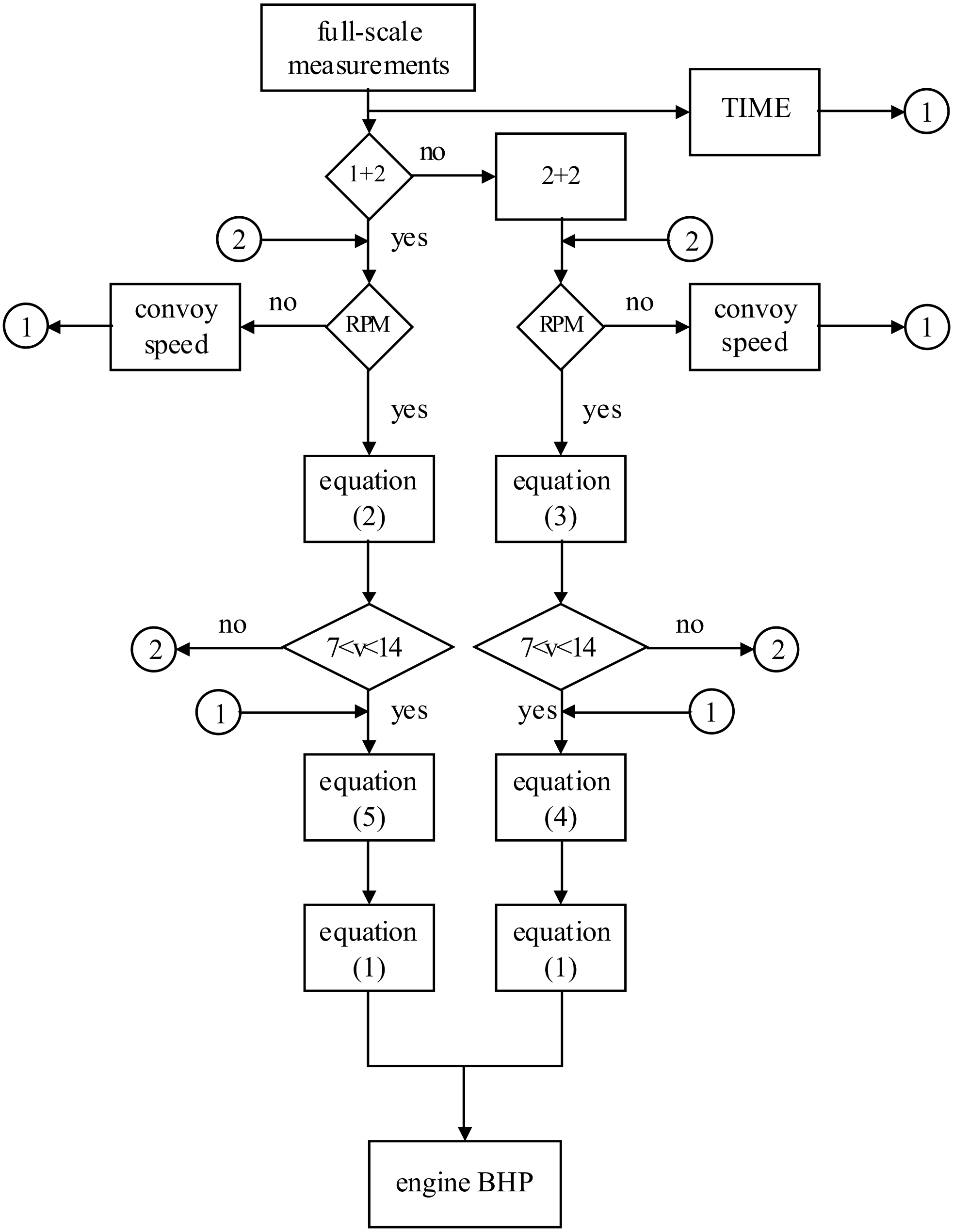

Fig. 5.
Operating Profile Flow Chart for "1+2" and "2+2" Formations of Barges

Table 2

Hourly and Specific Fuel Consumption for Both Pushboats and Both Formations

Brake power – directly at the engine (horsepower and kilowatt)		Fuel consumption (kg/h)	Specific fuel consumption (kg/kWh and kg/HPh)	
Pinki				
1006.5	739.8	170.8	0.169660	0.230830
925.9	680.5	156.8	0.169359	0.230421
815.1	599.1	137.7	0.168948	0.229861
1009.4	741.9	171.3	0.169671	0.230844
980.6	720.7	166.3	0.169563	0.230698
777.3	571.3	131.2	0.168808	0.229670
587.3	431.7	98.7	0.168108	0.228718
408.2	300.0	68.4	0.167462	0.227840
742.6	545.8	131.5	0.177113	0.240970
696.5	511.9	123.2	0.176934	0.240727
303.1	222.8	53.2	0.175455	0.238714
748.8	550.4	132.6	0.177137	0.241003
768.3	564.7	136.2	0.177213	0.241106
722.9	531.4	127.9	0.177037	0.240866
486.6	357.6	85.7	0.176129	0.239631
340.2	250.1	59.7	0.175587	0.238894
Panonija				
916.7	673.8	155.2	0.169325	0.230374
815.4	599.4	137.8	0.168949	0.229862
679.9	499.7	114.5	0.168448	0.229180
558.5	410.5	93.8	0.168002	0.228575
441.2	324.3	73.9	0.167580	0.227999
807.3	593.4	143.2	0.177365	0.241312
725.6	533.3	128.5	0.177047	0.240880
541.9	398.4	95.6	0.176340	0.239918
290.0	213.2	50.9	0.175410	0.238652
782.8	575.4	138.8	0.177269	0.241183
503.0	369.7	88.6	0.176192	0.239716
284.9	209.4	49.9	0.175392	0.238628
795.5	584.7	141.1	0.177318	0.241250
523.2	384.6	92.2	0.176268	0.239821
283.7	208.5	49.8	0.175388	0.238623

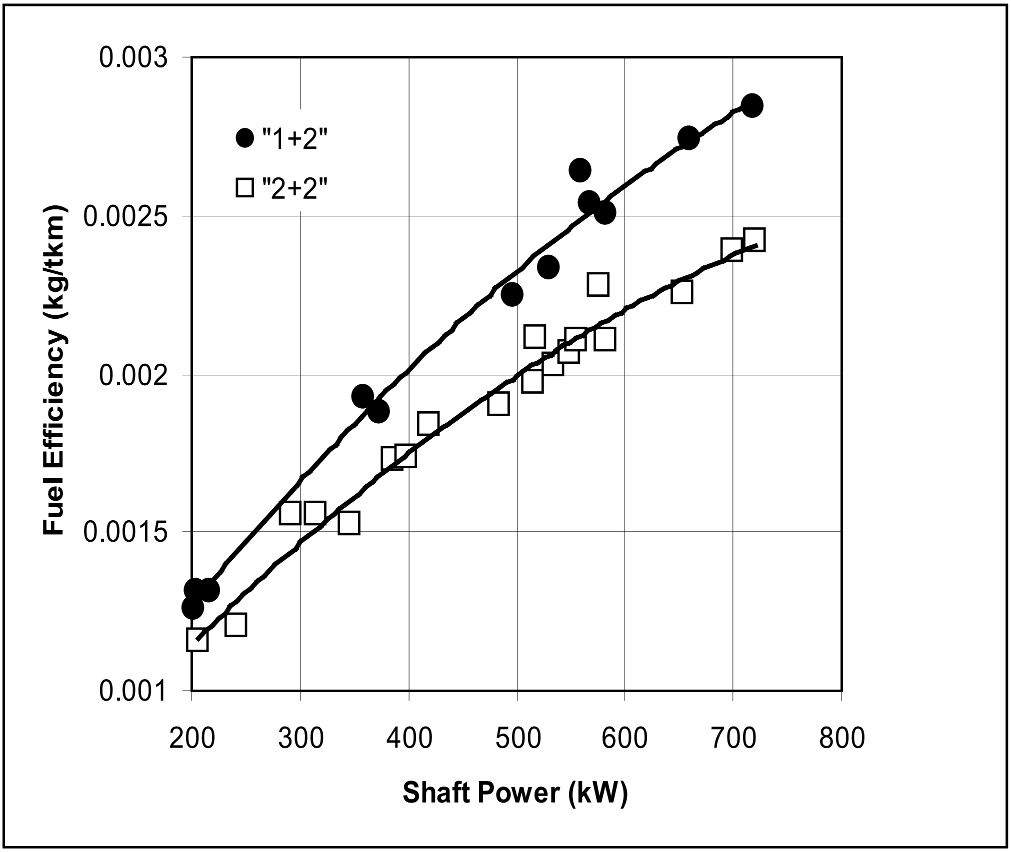

Fig. 6.
Comparison Between Two Barge Formations, Namely "1+2" and "2+2"

6. Conclusion

The implementation of the methodology for calculating fuel efficiency is an important first step in improving a strategy for overall decrease in pollution from ships. The effectiveness and simplicity of this new procedure should be evaluated through more full-scale measurement procedures. After the validation of the results for other Serbian pushboats, prediction methods for the relationship between speed and power should be developed. Fuel efficiency and transport efficiency should be calculated for each pushboat class. Following fuel efficiency determination, the comparison between different pushboat classes can be made for the same operating displacement. Travel time can be calculated using the information about typical distance data between ports.

The exact fuel savings would depend on the route and pushboat type and could be evaluated by the above proposed method.

Table 3

Transportation and Fuel Efficiency Summary

Total shaft power (kilowatt)		Fuel consumption (kg/h)	Specific fuel consumption (kg/kWh)	Transport efficiency (tkm/kWh)	Fuel efficiency (kg/tkm)
1+2	202.5	49.7508	0.23862	189.346	0.00126
	203.4	49.9688	0.23863	181.399	0.00132
	216.4	53.1855	0.23871	181.466	0.00132
	359.2	88.6335	0.23972	124.433	0.00193
	373.6	92.2306	0.23982	127.496	0.00188
	497.3	123.232	0.24073	106.998	0.00225
	530.3	131.53	0.24097	103.141	0.00234
	553.0	138.766	0.24118	91.4061	0.00264
	558.5	141.051	0.24125	95.0295	0.00254
	568.1	137.716	0.22986	91.7978	0.0025
	661.6	156.804	0.23042	84.1332	0.00274
	719.2	170.765	0.23083	81.11	0.00285
2+2	207.1	50.8772	0.23865	205.709	0.00116
	243.0	59.7362	0.23889	198.092	0.00121
	291.7	68.3563	0.22784	146.37	0.00156
	315.3	73.9448	0.228	146.743	0.00155
	347.5	85.6995	0.23963	157.075	0.00153
	387.0	95.5736	0.23992	138.828	0.00173
	399.1	93.8237	0.22858	131.733	0.00174
	419.7	98.7307	0.22872	124.337	0.00184
	485.8	114.528	0.22918	120.476	0.0019
	516.2	127.99	0.24087	121.966	0.00198
	518.1	128.472	0.24088	113.863	0.00212
	534.7	132.642	0.241	118.7	0.00203
	548.6	136.148	0.24111	116.654	0.00207
	555.5	131.221	0.22967	108.886	0.00211
	576.4	143.189	0.24131	106.042	0.00228
	582.7	137.77	0.22986	109.242	0.0021
	655.0	155.22	0.23037	102.133	0.00226
	700.7	166.267	0.2307	96.4778	0.00239
	721.3	171.266	0.23084	95.3667	0.00242

The results of such a programme may ultimately be substantial fuel savings as well as a decrease in pollution from Serbian pushboats.

The savings in costs for one shipping company could convince other companies or society to invest in river transport and utilize all the potentials that it has in comparison to other transport modes. Ships should improve the operational and environmental efficiency of their engines.

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STRATEGIJA ZA SMANJENJE ZAGAĐENJA KOJE STVARAJU POTISKIVAČI IZ SRBIJE

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Sažetak: Prevoz robe brodovima predstavlja efikasan način potrošnje goriva ukoliko se u razmatranje uzme pređena razdaljina po tkm, a svakako predstavlja vid prevoza kojim se najmanje zagađuje vazduh i životna sredina u odnosu na sve ostale vidove transporta. Dizel motori su već uveliko postigli efikasnost u potrošnji goriva i iako su (ovi motori) efikasni, ipak nisu beznačajan izvor emisije ugljenika na globalnom nivou. U ovom radu je predstavljena strategija za smanjenje ukupnog zagađenja s brodova kroz potrošnju goriva. Kombinovanjem karakteristika brodskog trupa i propulzionih osobenosti brodova pokazano je da postoji više mogućnosti za smanjenje zagađivanja sa brodova kroz smanjenje potrošnje goriva na brodovima. Studija se zasniva na eksperimentalnim ispitivanjima izgrađenih brodova pomoću torziometra i podacima dobijenih tokom merenja. Periodična ispitivanja snage i broja obrtaja na propelerskim vratilima mogla bi da omoguće posadama brodova predviđanje ponašanja brodova u eksploataciji kako bi minimizirali potrošnju goriva, a samim tim i smanjili zagađenje prirode i životne sredine. Koncept merenja brzine i snage broda na plovnom putu nije novi koncept. Predstavljeni su rezultati ispitivanja potiskivača koji pripadaju srpskoj floti. Rezultati su pokazali da bi ova procedura mogla da se primeni tokom određenog perioda u toku eksploatacije brodova.

Ključne reči: komponenta, potrošnja goriva, opsežna merenja, transportna efikasnost, efikasnost potrošnje goriva, brodska energetika.