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EXPERIMENTATION AND MEASUREMENTS ON THE PROPULSION PLANT OF A WATER BUS IN SERVICE ON THE "CANAL GRANDE" IN VENICE

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ABSTRACT

The demand for reducing the environmental pollution, together with the always present need of economy in the management of energy, leads to the improvement of existing systems and to the experimentation of new ones, capable of reaching these goals.

In this picture, a new research programme was carried out with the following main objectives:

- logging of characteristic working data of a ship;
- their analysis and organization so as to understand variation laws and trends;
- determination of main objectives of the management of a ship;
- study of the ways to reach such objectives;
- development of alternative propulsive solutions capable of obtaining the above mentioned results more completely.

The first step of this program was carried out on a "vaporetto" (water bus) moved by a diesel engine with a MCR of 135 kW @ 1800 rpm. Real working data of the propulsion have been logged on board during the service trough the Grand Canal of an instrumentated vessel.

Statistics of the power demand parameters were produced, showing the engine to work mainly far below its rating, which implies bad specific consumption and emissions.

Ways to improve such situation have been studied: among these, a hybrid diesel-electric system with batteries providing buffer energy storage. The diesel engine could be selected for a maximum output much lower then the present one, reducing the ratio between the peak and average output and making it operate at a few constant load set points, within a good efficiency and emissions range.

Besides a comprehensive discussion of data, the paper presents the results of the preliminary design of the hybrid system, based on state of the art components, and its prospected fuel consumption and emissions.

1. INTRODUCTION

The investigations illustrated in this paper are included in a wider research programme, involving public and private institutions, whose main target is the evaluation and optimization in the management of the propulsion plant of vessels belonging to fleets for various services.

The construction of a ship is not always followed by checking of the quality and stability of its performances; nevertheless, when it is possible to gather information about them, management improves in terms of a better possibility of intervention on maintenance and service policies, on cost foreseeing, on capability of carrying out alternative propulsive solutions suitable to the required service.

This work analyzes the navigation of vessels for public transport in inner and coastal waters when operational conditions become heavier because of the frequent running in transient state and environmental problems are more and more serious due to the continuous emission of exhaust noxious substances right next of inhabited zones with the consequent increased danger and undesirability.

In particular, the object of the present investigation are the vessels belonging to the ACTV (Azienda del Consorzio Trasporti Veneziano) fleet which supplies the public transportation in Venice.

The interest has been focused on water busses: in fact, due to the type of mission and propulsion plant, their engines are often forced to operating conditions far from the optimum ones, with the consequence of worsened consumption and emissions. In this picture it is possible to imagine a different kind of propulsion plant (and its management) conceived in order to optimize specific consumption and exhaust emissions for the type of service they have to supply.

2. EXHAUST EMISSIONS IN COASTAL NAVIGATION

The attention, that since the 60s has been given to the emissions of road-traction vehicles, is more and more extended to other fields where the risk of pollution by exhaust gases is an increasing concern.

In the marine field, however, the fight against environmental pollution caused by exhausts emissions from marine engines started with some delay; the approach to the problem is complicated by various circumstances:

- wide range of installed powers;
- different power releases depending on the running of the ship (displacement or planing);
- wide range of fuels used to supply marine engines.

Of course, the rules limiting the emissions from marine engines will be formulated in accordance with the know-how matured on road traction field. In fact, due to the closeness to inhabited centres and to the probable increase of this kind of navigation, a remarkable attention is destined now to the coastal traffic as an occasion of decongesting urban traffic within coastal sites.

Recently, the Lloyd Register of Shipping reported a survey on air pollution in the town of Vlissingen (Netherlands) in several weather conditions [Marine Exhaust Emissions Research Programme: Phase II - Summary Report. Lloyd Register of Shipping, London, 1993]. Although this town is characterised by a very strong maritime and coastal activity and is surrounded by a poor industrial settlement, the study of LRS (limited to the evaluation of the presence of NO_x and SO_2 in the air) reports that "the shipping makes a relatively minor contribution to the overall air pollution concentration".

Nevertheless, in a "town of water" like Venice, extremely rich in art works needing preservation, it is necessary to control the air pollution and, consequently, every source of it; Venice is a borderline zone between land and water and the lagoon transportation constitutes the real urban traffic. The operations of water busses are quite similar to the ones of road busses : the frequent "stop and go", the same kind of fuel (gas oil with S less than 0.3% in accordance with UNI/CUNA NC/630-01, 93-01-01) and other working modalities, put the two kinds of engine in similar operating conditions.

This justifies, more than in other circumstances, the extension to the marine field of the same methodologies consolidated in the road traction for the analysis, control and regulation of the emissions of ICE; in that context, the procedure universally used is the ECE-ONU R49 which includes the measure of the mass flow of NO_x ,CO , THC (total hydrocarbons), PM (particulate matter) emitted from the engine during the bench test carried out with a cycle of 13 load conditions considered statistically significant of the real mission of the engine ("13-modes method").

Of course, the mission profile used for road traction cannot be transferred "sic et simpliciter" to the marine field due to the different operating conditions occurring in the two cases; the effort to fit this kind of exhaust analysis, lead to the project ISO/DIS-8178 (and in particular its "cycle type E" specifically destined to marine engines), still in progress, which extends the same methodology of the "13-modes method" to marine engine, in search of a more suitable mission profile characterisation.

3. THE FLEET AND THE OPERATIONS OF VESSELS

The fleet of the ACTV is composed of six types of vessels referred to as follows: motor ship (M/N), ferry (N/T), water bus ("vaporetto", M/B), motor craft ("motoscafo", M/S), electric water bus (E/B), auxiliary vessel

(AUX). The following table shows the main characteristics of the elements of the fleet: because of the differences among vehicles belonging to the same group, the main values of variables are reported for each category or, when differences are too large, their maximum and minimum values.

type	n	Δ	grt	pass	v	lbp	P
M/N	12	123 - 206	155 - 292	640 - 1257	10.7 - 13	28.5 - 37.8	295-600
N/T	5	180 - 631	195 - 598	926 - 1500	10.5 - 12.8	40 - 54	295-880
M/B	54	37.5	24	220	11	21	135
M/S	59	21.2	23	155	11.5	20.8	135
E/B	1	32	24	208	9	20.9	60
AUX	22	1.2 - 127	3.7 - 184	-	8.6 - 38	7.5 - 36	63 - 147

n - number of vessels
Δ - displacement [t]
grt - gross register tonn
pass - max number of passengers
lbp - length between perpendiculars [m]
v - speed of the vessel [kn]
P - MCR of main engine [kW]

Tab. 1 - Characteristics of the ACTV fleet

The ACTV service supplies the public transportation both in the Grand Canal and between Venice and the lagoon islands; in particular, ferries and ships are destined to the far island allowing the transport of cars and heavy vehicles; water busses and motor crafts connect various canals of Venice and the near islands; the same mission is typical for the only existing electric water bus that, however, operates rarely due to batteries charging problems.

Fig. 1 gives an idea of courses in the Grand Canal and in the influent canals. The navigation in these sites,

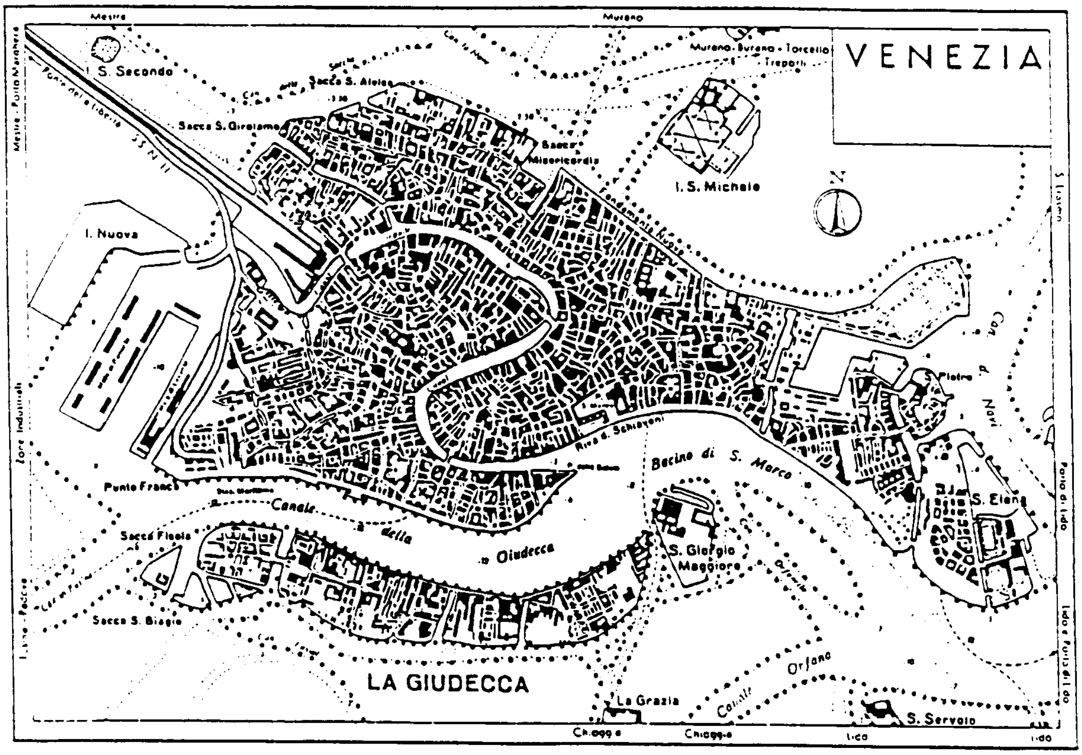

Fig. 1

which is the main object of this paper, is characterised by long operations in transient and few periods in permanent state, with frequent landing and unmooring and relatively long manoeuvring periods to respect the frequent stops and the possible concurrence of landing of other water busses; namely because of the particular characteristics of this service the attention of this work has been focused on the vessels destined to it.

4 THE MEASUREMENT SYSTEM

The data acquisition was carried out using a data logger (whose scheme is given in fig. 2) capable of receiving, analyzing and storing signals emitted in many standards used in data transmission today.

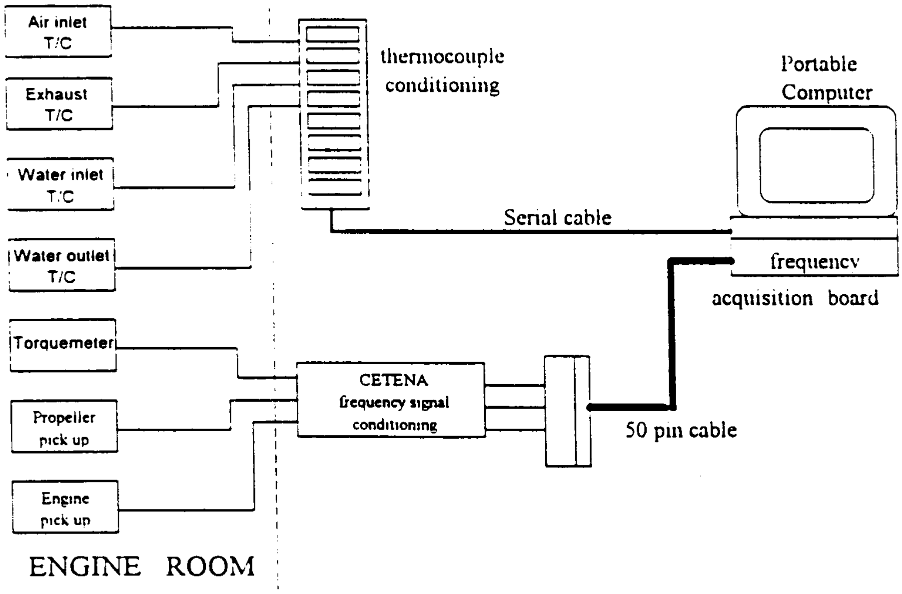

Fig. 2 - Data logger scheme

All measurement were made on the ACTV water bus (M/B) n. 54; table 2 shows, for each variable read, the sensor used and the respective reading error estimate:

variable	sensor	total error
exhaust temperature	thermocouple (K type)	± 1.5 °C
inlet water temperature	stickon thermocouple (J type)	± 1.5 °C
outlet water temperature	stickon thermocouple (J type)	± 1.5 °C
inlet air temperature	thermocouple (K type)	± 1.5 °C
engine torque	strain-gauge torquemeter unit	
engine rpm	pick-up	+ 1 rpm
propeller rpm	pick-up	+ 5 rpm

Tab. 2 - Data acquired on board during the line 1 service course

5. ANALYSIS OF THE RESULTS

The service track object of this first research phase is characterised by two main zones. One goes through relatively open waters facing the Venetian Lagoon and has stops fairly apart from each other. The other is totally in the Grand Canal and has very short distances between stops, sometimes around 100 m.

Data were recorded along three complete runs, two of which from the lagoon to the Grand Canal end, one in the reverse way. Each run had a duration of ca 1 hour, which implies a total of ca 7000 values per run of each parameter measured.

Fig. 3 shows the instantaneous power at the propeller shaft as function of time, relevant to the first half of the course. The corresponding course average power is ca 21 kW. The absolute maximum power is 84 kW and is relevant to an acceleration phase in the first phase of the recording when the vessel run in open waters. Isolated short peaks of similar magnitude were recorded all along the track either in acceleration or in reverse rotation to break at the stops. This similarity of peak patterns, being typically generated by very brief transients, was confirmed by the other recordings, even when the captain had a smoother powering attitude.

The propeller shaft power statistics of the above recording is reported in Fig. 4. This shows the extreme underutilisation of the engine, which is rated at ca 160 kW at the flywheel and could reach 130-140 kW at the propeller shaft, upstream the hull seal. The figure not only shows the average to be less than 20% of the rating, but also that the most frequent power range falls further below: the useful power is lower than 5 kW for ca 20% of the time and lower than 10 kW for ca 30% of the time.

Sustained relatively high power levels fall only around 60-65 kW, corresponding to the demand at the critical vessel speed, occurring mostly in open waters; this is shown in Fig. 5, where the power-rpm data recorded in this same run at the propeller shaft are scattered, overlapped with the two cubic functions, which best fit the data acquired under previous stationary tests, respectively at the bollard and in forward motion.

Still from Fig. 4 it can be seen that peaks exceed the 65 kW threshold, corresponding to 50% of engine rating, for less than 2% of the time.

Other statistical analyses made on the recordings show that the engine and the propeller rotation speed averaged ca 1050 and 240 rpm respectively, with peaks of 1700 and 415 rpm.

It must be noted that the vessel was not at its highest load during the measurements, since it featured a redundant service on the line, and that environmental conditions were favourable, with calm water and low breeze. Caution should thus be paid in extrapolating, at the present stage of the work, the above statistics to the year round operation of the whole fleet. Yet some preliminary comments are possible on the implications and remedies on fuel consumption and emissions; peak and average values can indeed be expected to be less than proportional to payload or wind and wave conditions.

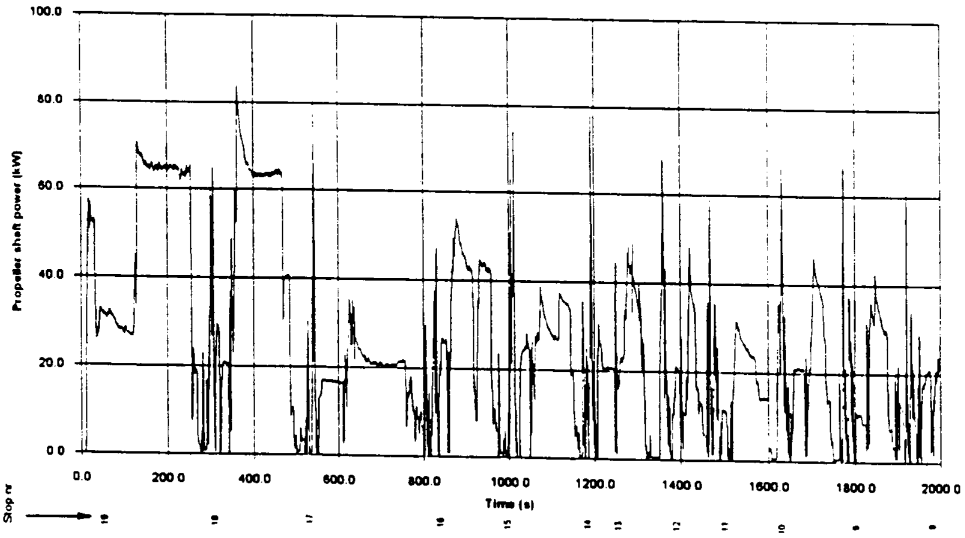

Fig. 3 - Recorded propeller shaft power during the first half of the line 1 course

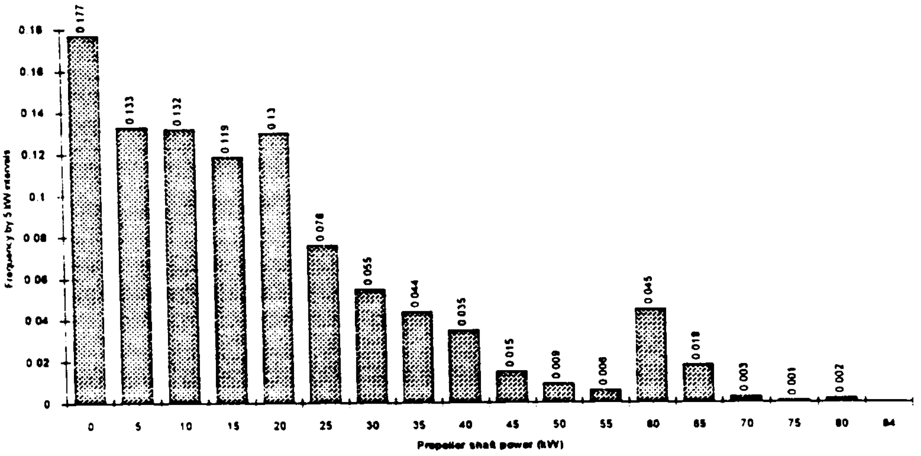

Fig. 4 - Propeller shaft power statistics (whole line 1 course, i.e. 3600 s)

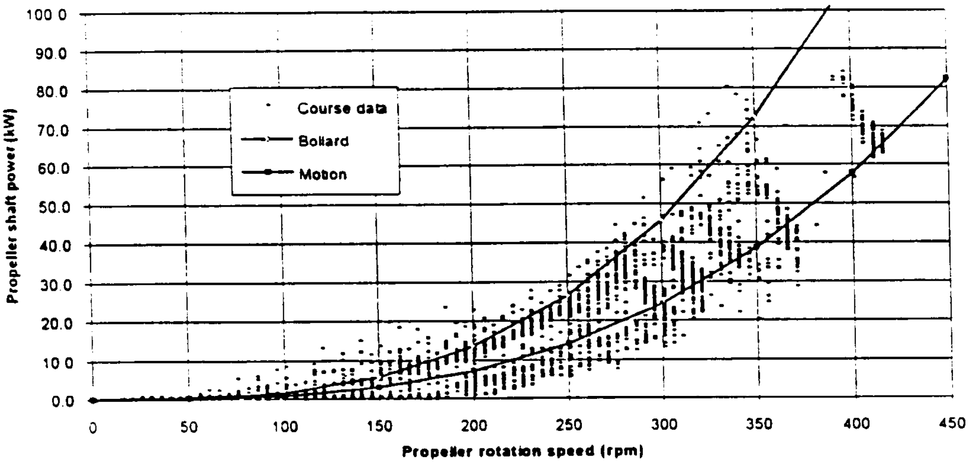

Fig. 5 - Propeller shaft power vs rotational speed scatter diagram

6. IMPLICATIONS OF PRESENT WATER BUSSES MISSION PROFILES ON FUEL CONSUMPTION AND EMISSIONS

The results reported in section 5 are not surprising. Indeed propulsion systems must be designed to safely cope with unforeseen circumstances and feature effective breaking capability to manoeuvre. However the prevailing under utilisation of the engine implies it to mostly operate in the high fuel consumption and emissions range, as typically shown in Figs. 6 to 9, where dimensionless BSFC, NOx, CO and HC are plotted vs. the dimensionless power. In all figures the normalising parameters are those measured at the maximum torque (C_0) and speed (n_0) or when:

$$P* = \frac{P}{P_0} = C * n* = \frac{C}{C_0} \frac{n}{n_0} = 1$$

These figures show results from the ECE-ONU R49 tests and best fit single variable polynomials, each relevant to two turbocharged engines having max power rating close to the 54 M/B. Of course all these parameters depend on both torque and speed independently, as implied in the data splitting apart of the relevant interpolating curve. Moreover the 54 M/B engine is not turbocharged and its emissions patterns may be different. Yet this single variable relationship, which reasonably fits data of two totally different engines, can be used to show qualitative but sensible implications of present engine utilisation and of the choice of a different power system on the overall fuel consumption and emissions.

With the polynomial functions extracted from these data and the statistical power distribution of Fig. 4 the contribution of each power interval to consumption and emissions has been evaluated obtaining results like those in Figs 10 and 11, where the sole FC and CO data are reported for briefness.

The most relevant results are the ratios between the average consumption and emissions, corresponding to each parameter distribution, and the respective values featured by the engine at the maximum power (referred to as nominal value). These results are summarised in Tab. 3 and show the significant penalisation due to the power utilisation pattern.

Parameter	Ratio = Average/value at max P
Fuel consumption	1.80
NOx emission	1.28
CO emission	2.57
HC emission	6.76

Tab. 3 - Estimated overall performance of the 54 M/B.

These figures are preliminary and qualitative and will be updated soon after completion of the next on-board and bench experimental phase, when the actual consumption and emissions of the 54 M/B engine will be measured under all conditions.

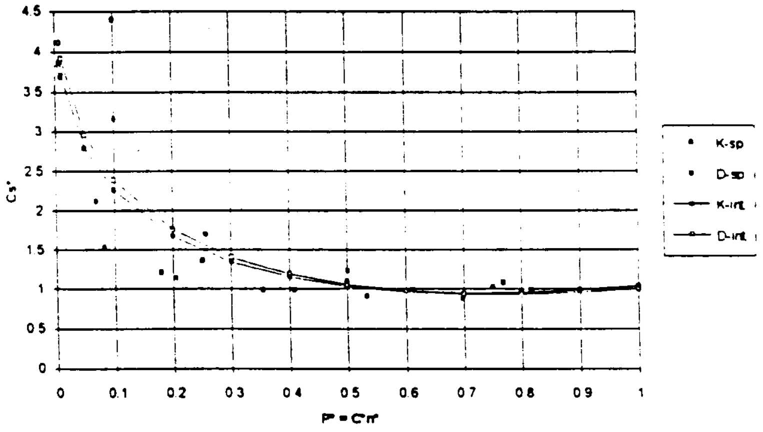

Fig. 6 - Relative variations of the specific fuel consumption with power for two commercial engines (dimensionless values).

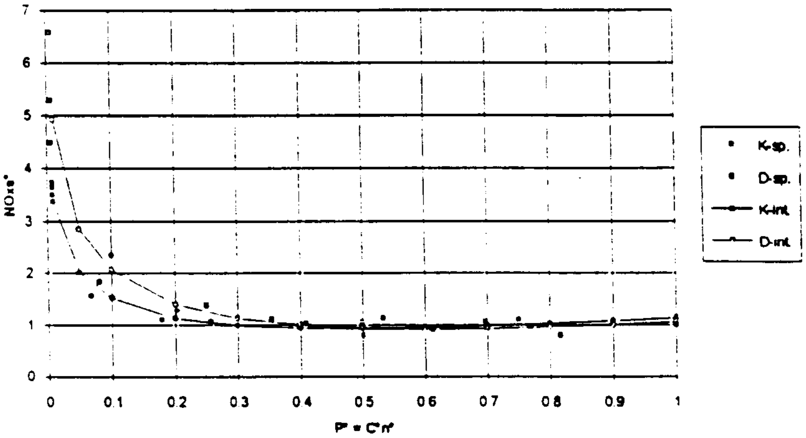

Fig. 7 - Relative variations of the specific NOx emission with power (dimensionless values).

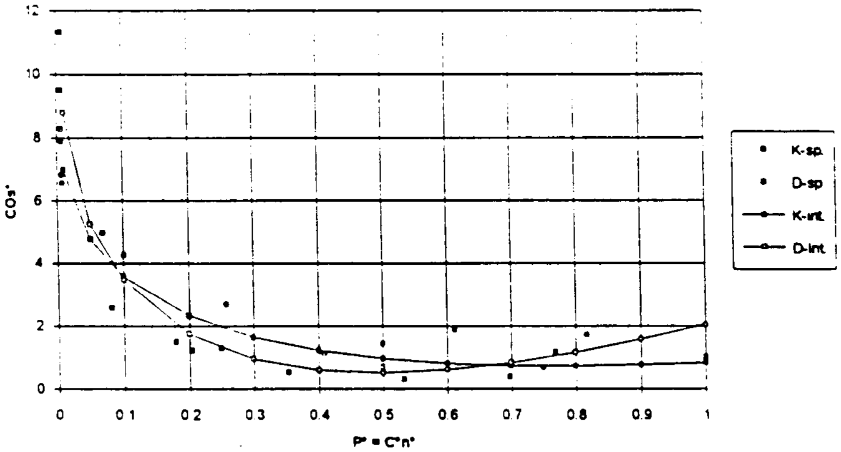

Fig. 8 - Relative variations of the specific CO emission with power (dimensionless values).

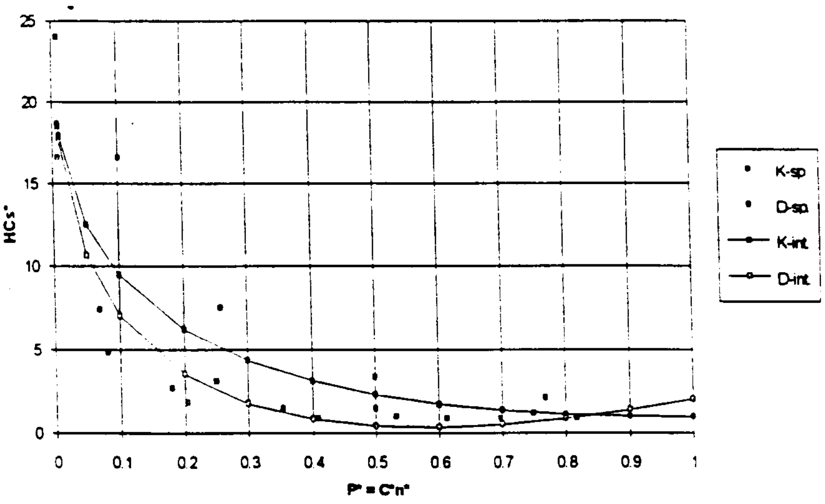

Fig. 9 - Relative variations of the specific HC emission with power (dimensionless values).

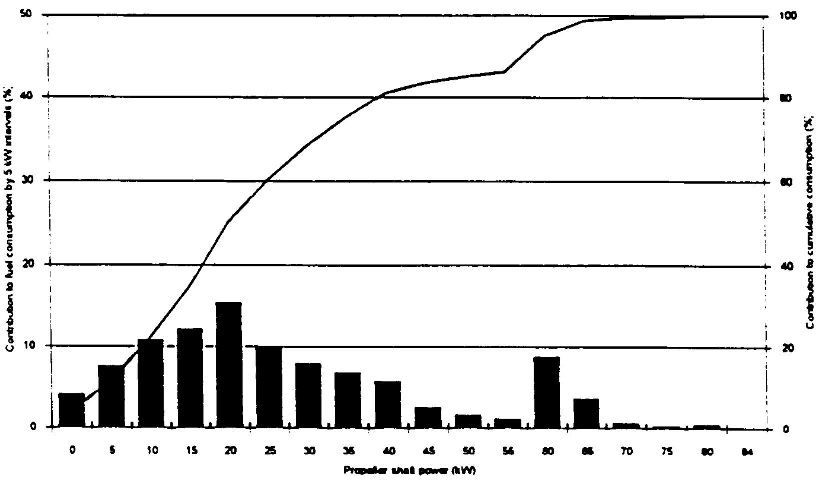

Fig. 10 - Fuel consumption distribution for the Grand Canal navigation

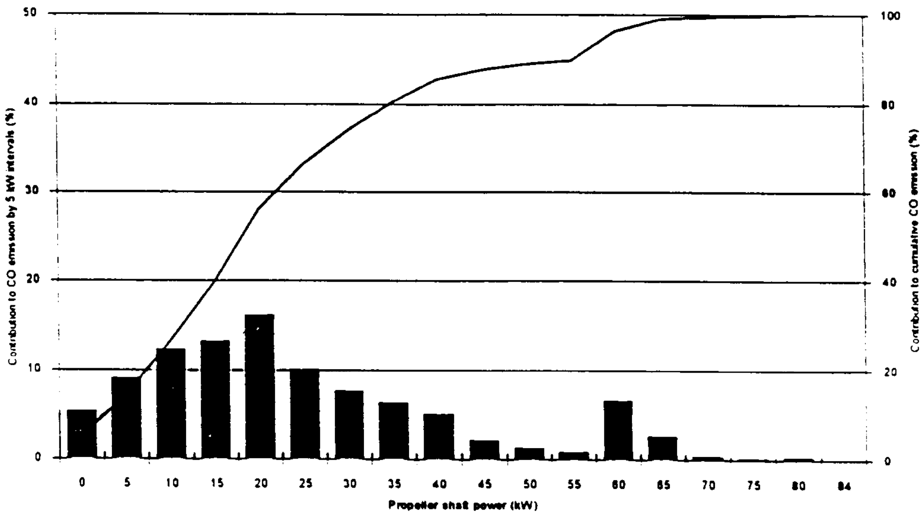

Fig. 11 - CO emission distribution for the Grand Canal navigation.

7. ALTERNATIVE ENERGY SYSTEMS

The work is focused to comparing ways to reducing consumption and emissions by either of the following solutions:

a. Selection of a smaller engine and azimutal propeller, with power output servo-control to optimise and reduce peak power demand during transients;

b. Hybrid diesel-electric with smooth continuous engine modulation;

c. Hybrid diesel-electric with fixed engine operating points;

d. Combination of "a" with the best between "b" and "c".

The discussion which follows concentrates on the results obtained so far for "b" and "c".

Hybrid diesel-electric with smooth continuous engine modulation

A possible configuration of diesel-electric hybrid power system is shown in Fig. 12. Other architectures are possible, e.g. with an inverter and a.c. motors instead of the d.c. motor drive.

To identify the design data for a system based on solution "b" a reanalysis of the data recorded in the Grand Canal navigation (see Fig. 3) was performed based on a *mobile average smoothing* of the power profile. A comparison of results obtained by setting the averaging time base alternatively to 30, 60 and 120 s showed that an optimum trade-off between the energy capacity and the peak power of the generating set is obtained with the 60 s mobile average. Under this hypothesis the control of the diesel engine could be performed by allowing its power to smoothly vary within a reduced range, following the last minute average of the actual demand, indirectly measured by the electric motor control signal. This approach leaves the possibility to match peak power demand corresponding to the recorded course, yet limiting batteries discharge, thus consequent capacity requirement, when relatively high power levels are sustained for long.

The statistical distributions of the mobile average shaft power (in charge of the diesel engine) and the buffer power (i.e. the net shaft power exchanged between the batteries and the system) are shown in Figs 13 and 14. The maximum shaft power demand at the propeller would now be reduced to 67 kW, instead of 84 kW (-20%) of present configuration, but, most importantly, the large share of low load levels (i.e. below 15 kW) is drastically reduced. This allows to expect that both fuel consumption and emissions would improve significantly.

Indeed with these different statistics and an engine rated to 70 kW instead of present 160 the figures of Tab. 3 would change as per Tab. 4. This preliminary evaluation has been made assuming that also this smaller engine follows the relative variation characteristics of Figs 6 to 9 and that the average efficiency of the electric system is 70% (average of the various operating modes along the navigation) as compared to an estimated 90% for the present mechanical transmission.

Parameter	Ratio = Average/value at max P	Relative variation (%)
Fuel consumption	1.72	-5
NOx emission	1.36	+5
CO emission	2.06	-21
HC emission	5.17	-24

Tab. 4 - Potential overall performance of the 54 M/B with a *Modulated Hybrid System*.

Despite the improvements obtained by this solution a spread remains between the maximum power demand and the average (ca 3.25:1 ratio), which affects the performance at low load.

Hybrid diesel-electric with fixed engine operating points

An alternative solution, referred to as "c" above, is to keep the engine set at few fixed working points, following the navigation phase, switching among those by smoothed steps.

One possible stepwise management of the power profile of Fig. 3 is shown in Fig. 15 (smoothing is not shown), where the engine load is set to either 40, 18 or 14 kW at the propeller shaft, that would correspond to 57, 26 and 20 kW at the engine, considering the same average efficiency of solution "b" of 70%.

The figure shows also the net power exchange with the buffer system and its integral function E_s which determines the batteries net charge-discharge cycles, or in formula:

$$E_s(t) = \int_0^t \left(P(t) - \overline{P(t)}\right) dt$$

where $\overline{P(t)}$ is the stepwise power level at the propeller shaft, equivalent to the engine load.

The respective shares of the three levels are 17, 58 and 25 %, giving the same course average of 21 kW at the propeller. Assuming to select the engine rating for the maximum of these levels (57 kW instead of present 160 kW) the overall relative performance in terms of emissions and consumption all along the course would become as summarised in Tab. 5.

Parameter	Ratio = Average/value at max P	Relative variation (%)
Fuel consumption	1.43	-20
NOx emission	1.26	-1.5
CO emission	1.44	-44
HC emission	3.39	-50

Tab. 5 - Potential overall performance of the 54 M/B with a *Step Mode Hybrid System*.

The advantages obtained shall be highlighted in that no modification of the power demand profile has been assumed. Should an optimum control of the thrust be implemented in the vessel, i.e. also incorporating solution "a", a further reduction of emissions and fuel consumption could be achieved, since the max/average power ratio would be reduced even more, this being the most important parameter.

Batteries main characteristics

A preliminary dimensioning of the electric batteries has been made, based on the solution referred to as "b" and on the consequent electric power demand.

A comparison between high discharge Ni-Cd, Lead-Acid batteries and other off-the shelf options concluded that the former are preferable for naval propulsion and give the characteristics summarised in Tab. 6, which were derived with a capacity reserve factor of 2 over the maximum buffer energy requirement.

With solution "c" a moderate increase of energy buffer requirement may be necessary, which however seems not to affect significantly the feasibility of the hybrid propulsion.

Voltage	240 V
Gross capacity (C/I = 5 h)	64 Ah
Actual capacity utilisation	12 Ah
1 min current (power)	256 A (61 kW)
1 s current (power)	423 A (102 kW)
Total mass	1200 kg
Total volume	600 lt

Tab. 6 - Summary data of Ni-Cd batteries for the hybrid system.

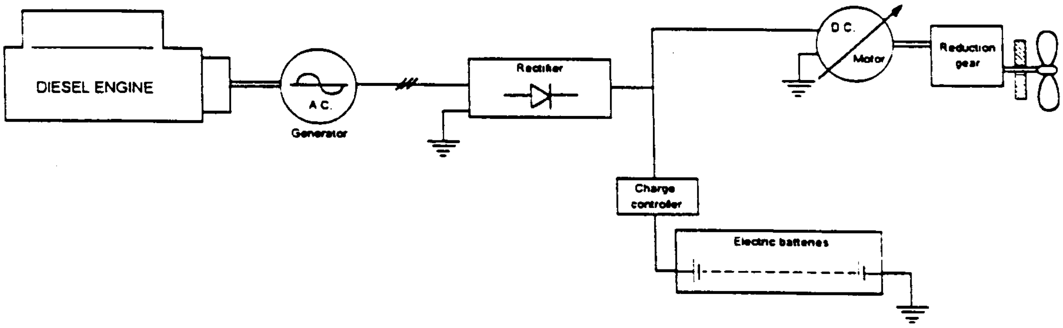

Fig. 12 - Scheme of hybrid power system

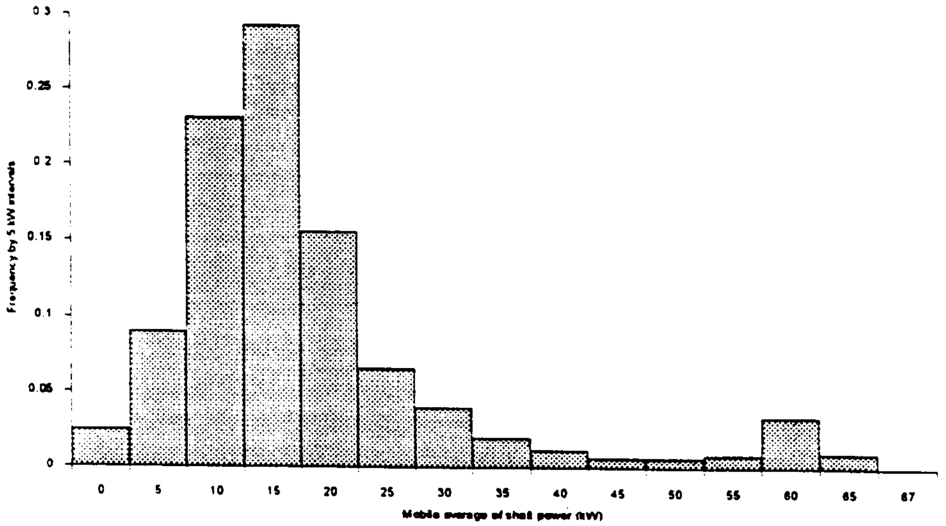

Fig. 13 - Statistical distribution of the 1 min mobile average power derived from Fig. 2,a-b.

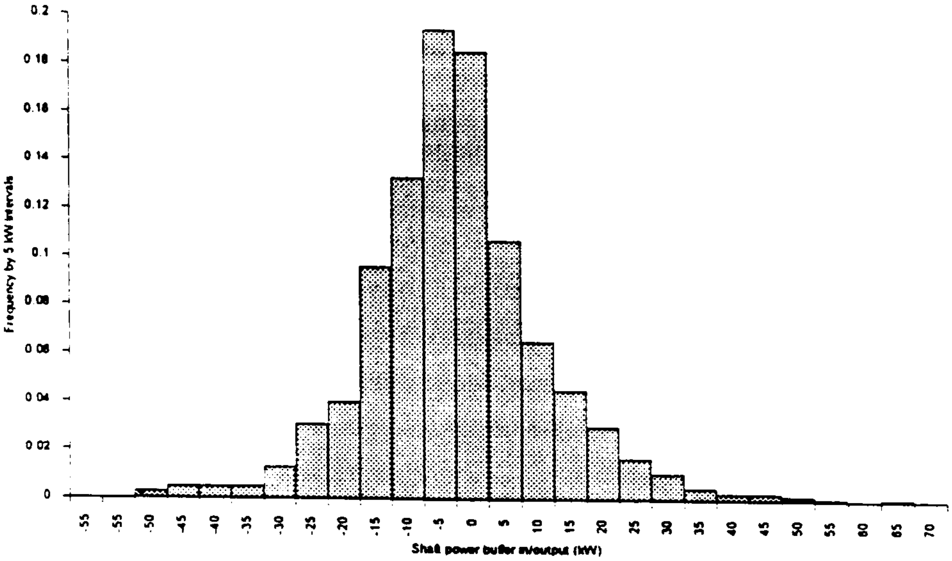

Fig. 14 - Statistical distribution of the buffer power in/output.

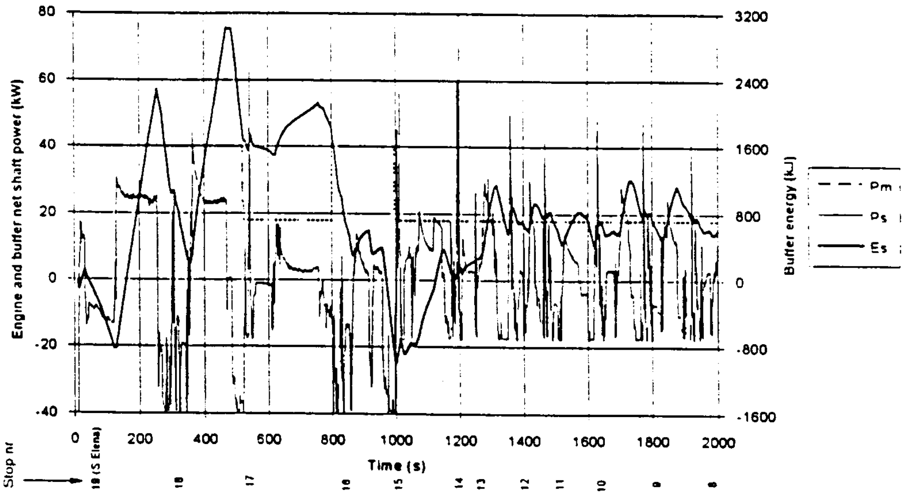

Fig. 15 - Engine power (Pm), Buffer power (Ps) and Buffer energy (Es) based on the course data of Fig. 3

8. CONCLUSIONS

The analysis of the power demand during a typical service course of a waterbus in the Venice city showed a marked under utilisation of the engine capability, which implies bad actual fuel consumption and pollutants emission compared to those obtainable by the same type of engine if it worked closer to the nominal operating point.

The research identified potential savings in fuel and emissions, which could reach 40 to 50% respectively for CO and HC, by replacing the present diesel propulsion rated at 160 kW with a diesel-electric system with the engine set to work at few constant loads, between 20 and 60 kW.

Further reduction of consumption and pollution could be obtained if the hybrid system approach, with its understood advantages in terms of noise/vibration-free operation, would be combined with approach "a", i.e. by adding a servo controller to provide an optimum power output and an improved azimutal propeller, in order to reduce the present power peaks.

The figures reported in this paper, which are preliminary, will be updated at completion of the data acquisition on the engine, both on board and on the break bench, above all after check of the mechanical efficiency of the transmission all over the working range and after deeper study of the electric system.

ACKNOWLEDGEMENTS

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