The propulsion of public transport vessels in coastal and inner waters: working data acquisition, elaboration and study of alternative solutions

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1- Abstract

The existing energy systems, especially if designed some time ago, may not fit the progressively restricted limits of pollutant emissions and can be unsatisfactory from the point of view of their energy consumption.

This is the reason why three Italian Organisations (*Dept. of Naval Engineering* - Naples, *CNR Istituto Motori* - Naples and *Systems and Advanced Technologies Engineering* - Venice), in co-operation with the ACTV (the Venetian public transport Company) are involved in a common research programme on the working conditions of a vessel of the ACTV fleet.

The main goal of this research is the evaluation of the operations of a boat in regular service by analysing the results of a campaign of data logging: thus, the paper describes the instrumentation on the boat and the boundary conditions of the campaign giving a critical report of the analysis of the collect data.

On the basis of the figures obtained, a project of an alternative energy management system for the boat is now in progress with the aim of complying with the severe limits of the main emissions which will be probably fixed by the involved Authorities in the near future. An outline of this activity will be given together with the first results of the elaboration completed up to now.

2 - Introduction

The present work has been stimulated by the simple following consideration: *small self traction engines are generally directly coupled with the final user (wheels, propellers etc.), therefore there is a remarkable difference between the mean power used for the propulsion and the maximum rating of the engine.* This causes several negative consequences:

- the engine is oversized in comparison with the main rating required and its under-utilisation means higher initial and maintenance costs;
- its working conditions are very different from the nominal ones; this means worse fuel consumption and emissions which rise to rather higher levels than the ones they could reach in better operational conditions.

Although the former condition creates only economic problems, the latter may cause pollution in proximity of inhabited sites and, in this sense, is to be considered as source of environmental danger. Moreover, a high level of emissions might create some problem in coping with limits to emissions which sooner or later will be adopted by local authorities especially for the navigation, coastal and in inner waters.

This problem, which generally does not affect marine engines (working close to their nominal conditions) but does affect most part of the road traction engines, turns out in a very peculiar (and exceptional) marine case: the public transport in Venice lagoon where people movement is granted by relatively small boats which operate almost in the same way as the urban busses do.

In the first phase of this research programme (November 1993), some recordings of the power profiles were carried out; since it was not possible at the time to log fuel consumption and noxious emission data on board, such characteristics were foreseen on the basis of a comparison with the ones of a similar engine, by applying it the same load profile. Afterwards, a more complete campaign of data logging (including the recording of consumption and emissions) took place in May 1994. This paper describes basically the latest elaboration of such data.

Due to the particular conformation of the Venetian lagoon, urban service is supplied only by means of marine vehicles: the fleet of the ACTV (Associazione del Consorzio dei Trasporti Veneziano) company, is composed by six kinds of vessels to cope with different needs of people and vehicle transport. Vessels are 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).

Table 1 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 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
v - speed of the vessel [kn]
lbp - length between perpendiculars [m]
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 islands for 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 being an experimental prototype.

3 - Data logging and test conditions

In order to reveal the operative characteristics of the fleet , a complete screening of the real working parameters was performed by carrying out a number of tests on a unit in regular service on the main routes of the Venetian lagoon; water busses and motorcrafts were considered as the most representative vessels of the fleet because of their number, transport capacity and routes covered, which force them to the poor operational conditions described before. Thus, the ACTV M/B n. 54 was instrumented so as to record, in real time and every 0.5 s, the following parameters:

engine torque
engine rpm
exhaust temperature
propeller rpm
engine water inlet temperature
engine water outlet temperature
engine air inlet temperature
engine air outlet temperature
injection pump position (load indicator)
speed of the vessel
gaseous emissions (NO_X , HC , CO)
smoke

The characteristics of vessel and engine are shown in table 2 together with the test conditions.

M/B 54 (construction year : 1935)	**Reduction-inversion gear**: Lohman GUS 200
Lbp = 20.91 m	reduction ratio = 4:1
Δ = 38.7 t (with no passengers)	**Propeller**: 3 blades (right)
v = 11 kn	D = 1000 mm
max passenger number: 224	p = 1000 mm
Engine: IVECO ***aifo*** M821	hull conditions: limit of classification (very dirty)
MCR: 135 kW @ 1800 rpm	

Tab. 2 - Characteristics of the M/B 54

The instantaneous value of the power, of course, was obtained by multiplying the torque and rpm values; displacement, sea and air temperature, wind speed were also recorded, although not automatically.

Tests were carried out on service on lines 1 and 82 which were considered as the most representative ones from the point of view of covered routes, number of passengers moved, number of stops, in other words, of operational strength. Each route was covered several times in different periods of the day, with different Captains and number of passengers. Tests were taken also on bollard and in free water.

The hull of the tested boat was in very bad conditions (at the end of its classification time) and thus the power required was higher than the one which would be necessary in better hull surface conditions.

The data logger is based on several sensors, each aimed at reading one parameter to be logged, linked to a system which provided multiplexing, conditioning, A/D conversion (when necessary), and storage of collected data.

The results of this campaign consist of several files in which each record contains the time of logging and all the variables read in a format immediately usable for the following elaboration.

4 - Analysis of the power demand

So as to represent the load profiles of the propulsion plant under exam, one record for each line is reported, since records logged on the same line, and the corresponding power distributions, are practically identical.

Figures 1 to 8 show the propeller shaft power release in time and its distribution for each of the main routes followed by Venetian boats in service together with related main statistics.

Line 1 is characterised by a very low ratio between stationary and transient state periods; this causes a considerable concentration of ratings between 0 and 50 kW (for more than 70% of the time the power release is included between these values and the average power is about 37 kW) with an evident under - utilisation of the engine whose maximum rating is 135 kW. A high power request falls only around 75 kW corresponding to relatively high vessel speed in free water (transfer from S. Zaccaria to Lido which is the only section while the vessels run in relatively open waters). Ratings of over 75 kW (i.e. less than the 60% of maximum engine power) are required only in manoeuvring transients and for short time periods (less than the 10% of the time).

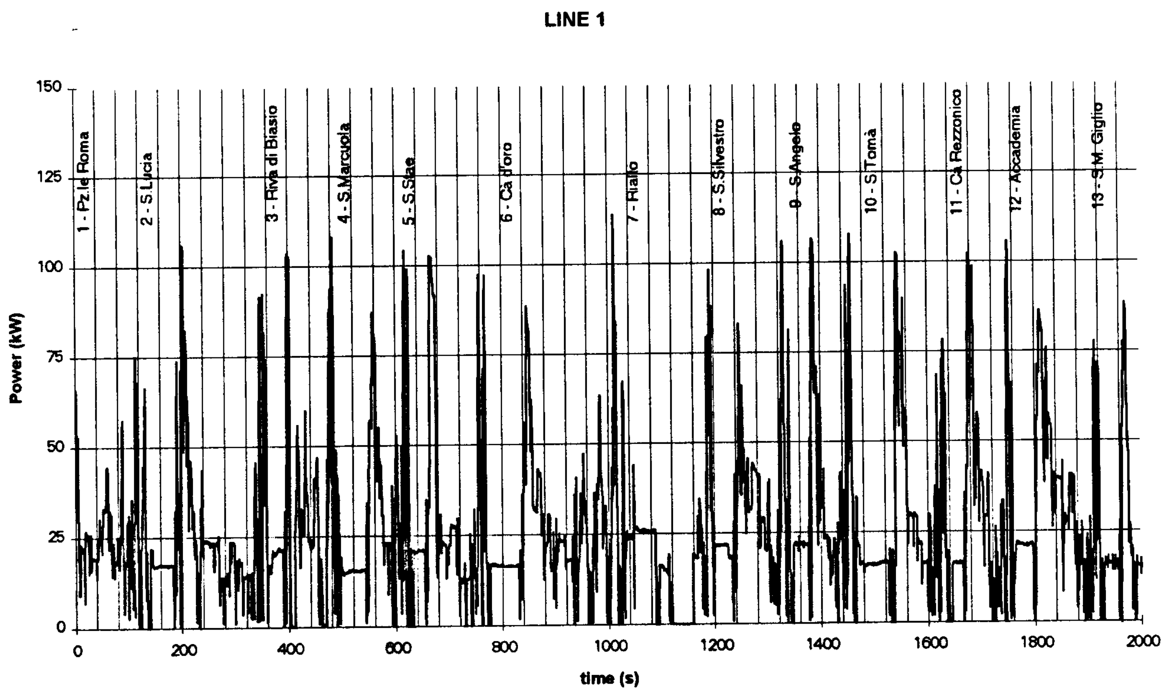

Fig 1 - Recorded propeller shaft power during the first half of the line 1 course (P.le Roma - S. M. del Giglio)

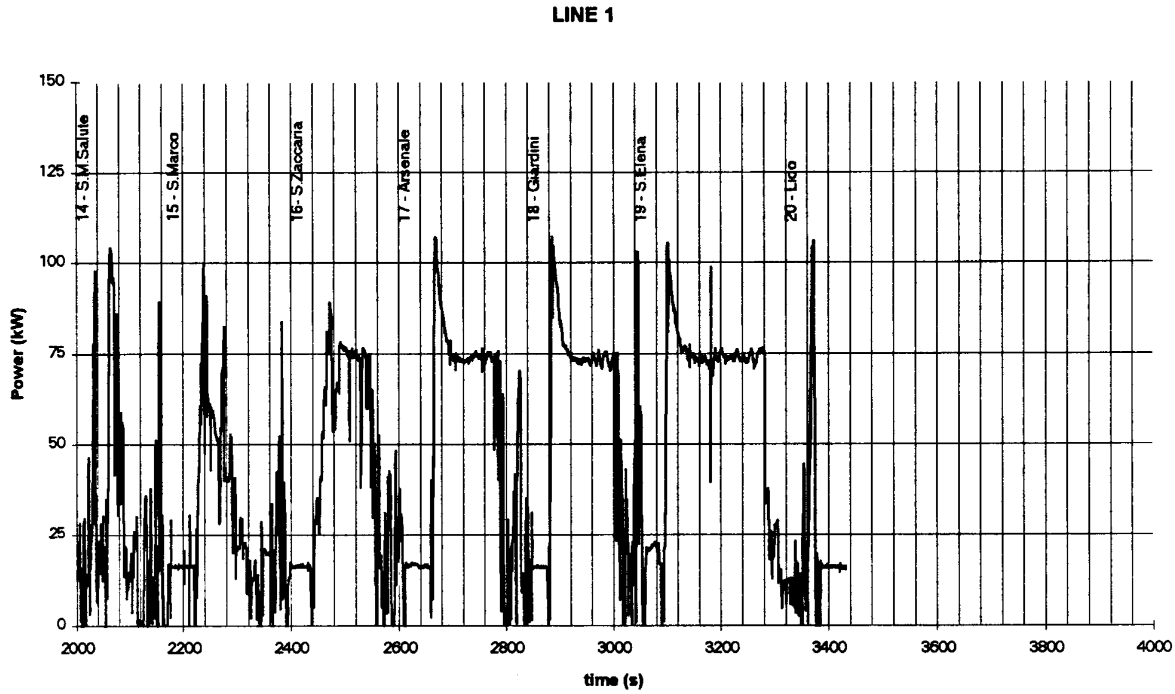

Fig 2 - Recorded propeller shaft power during the second half of the line 1 course (S. M. Salute - Lido)

PROPELLER SHAFT POWER STATISTICAL ANALYSIS
Absolute Power (kW)

LINE	1 (Grand Canal)		
FILE	CR30		
MAXIMUM		113.6	
MINIMUM		0.0	
AVERAGE		33.6	
VARIANCY		26.3	
MEDIAN		22.5	
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.083
	5	0.083	0.033
	10	0.116	0.080
	15	0.196	0.218
	20	0.414	0.135
	25	0.549	0.071
	30	0.620	0.045
	35	0.665	0.031
	40	0.696	0.036
	45	0.732	0.017
	50	0.749	0.017
	55	0.766	0.019
	60	0.785	0.014
	65	0.799	0.013
	70	0.812	0.092
	75	0.904	0.042
	80	0.946	0.013
	85	0.959	0.010
	90	0.969	0.008
	95	0.977	0.008
	100	0.985	0.011
	105	0.996	0.003
	110	0.999	0.001
	114	1.000	

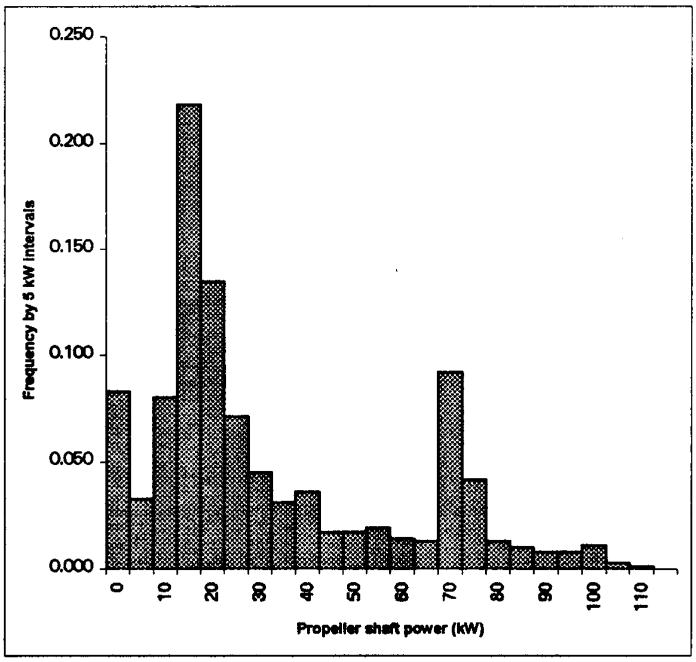

Fig 3 - Power distribution (line 1)

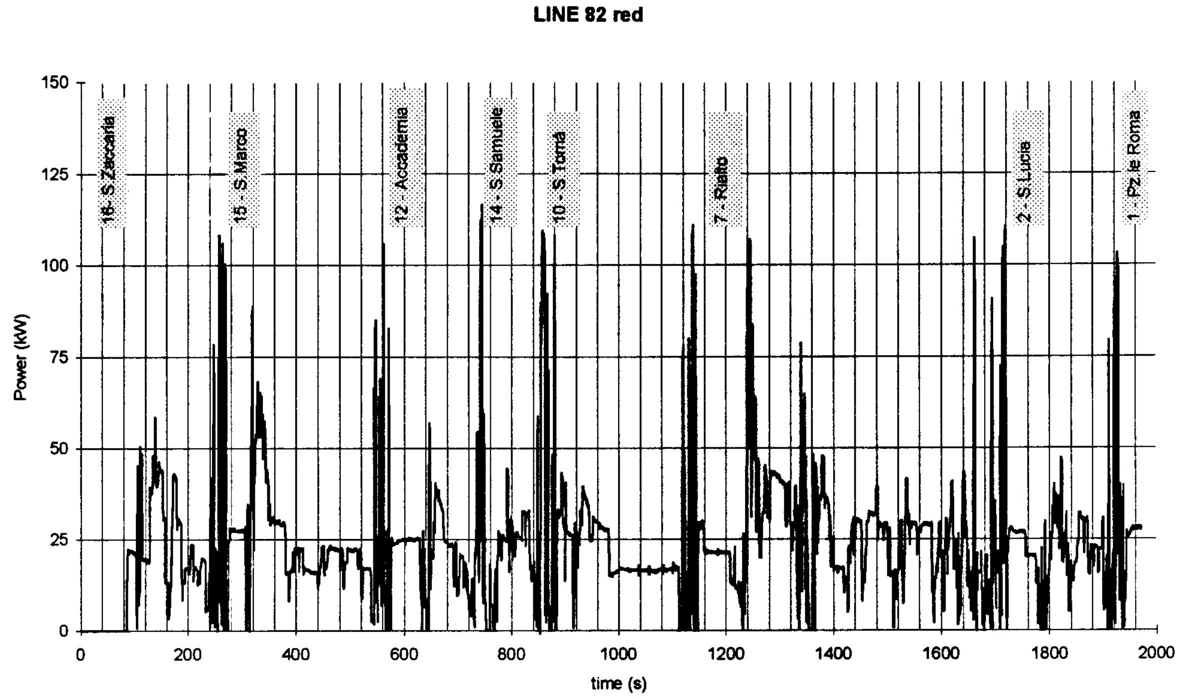

Fig 4 - Recorded propeller shaft power during the line 82 red course (S. Zaccaria - P.le Roma)

PROPELLER SHAFT POWER STATISTICAL ANALYSIS
Absolute Power (kW)

LINE	82 (Grand Canal)		
FILE	CR70		
MAXIMUM		116.2	
MINIMUM		0.0	
AVERAGE		23.8	
VARIANCY		16.8	
MEDIAN		22.0	
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.100
	5	0.100	0.057
	10	0.157	0.071
	15	0.228	0.195
	20	0.423	0.175
	25	0.598	0.182
	30	0.780	0.073
	35	0.853	0.037
	40	0.890	0.043
	45	0.933	0.015
	50	0.948	0.008
	55	0.956	0.008
	60	0.964	0.007
	65	0.971	0.003
	70	0.974	0.003
	75	0.977	0.003
	80	0.980	0.002
	85	0.982	0.002
	90	0.984	0.003
	95	0.987	0.003
	100	0.990	0.004
	105	0.994	0.004
	110	0.998	0.001
	115	0.999	0.001
	116	1.000	

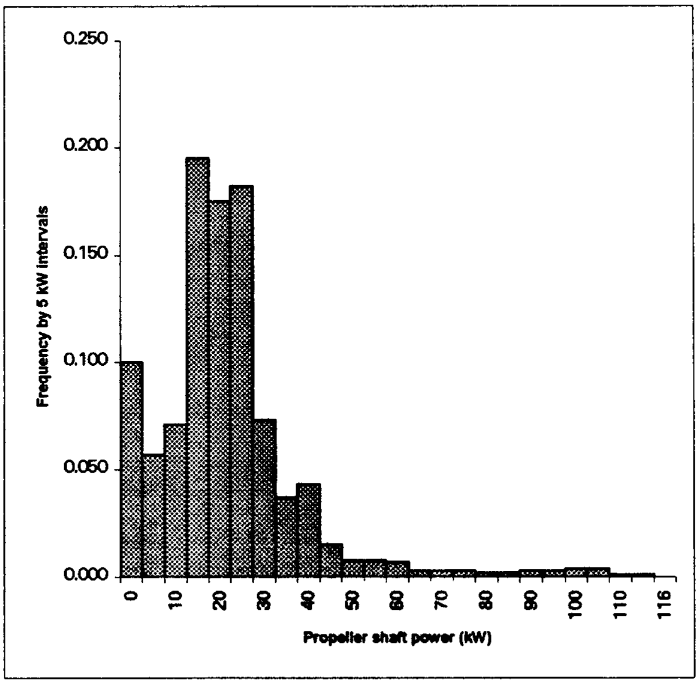

Fig 5 - Power distribution (line 82 red)

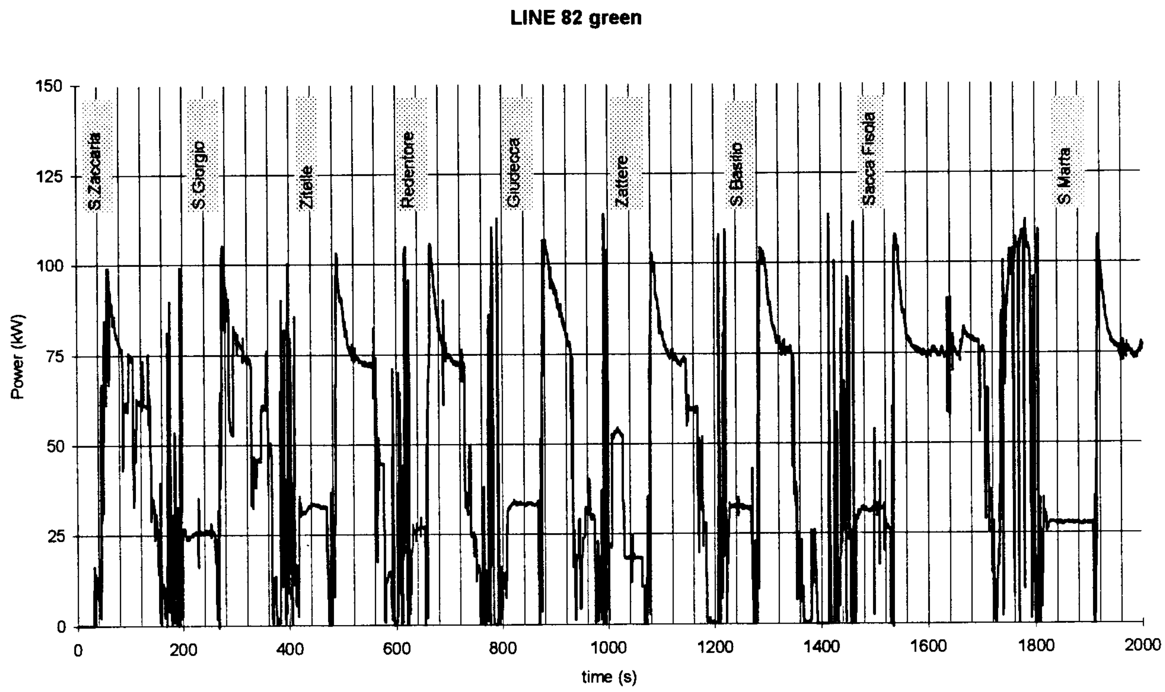

Fig 6 - Recorded propeller shaft power during the first half of the line 82 green course (S. Zaccaria - S. Marta)

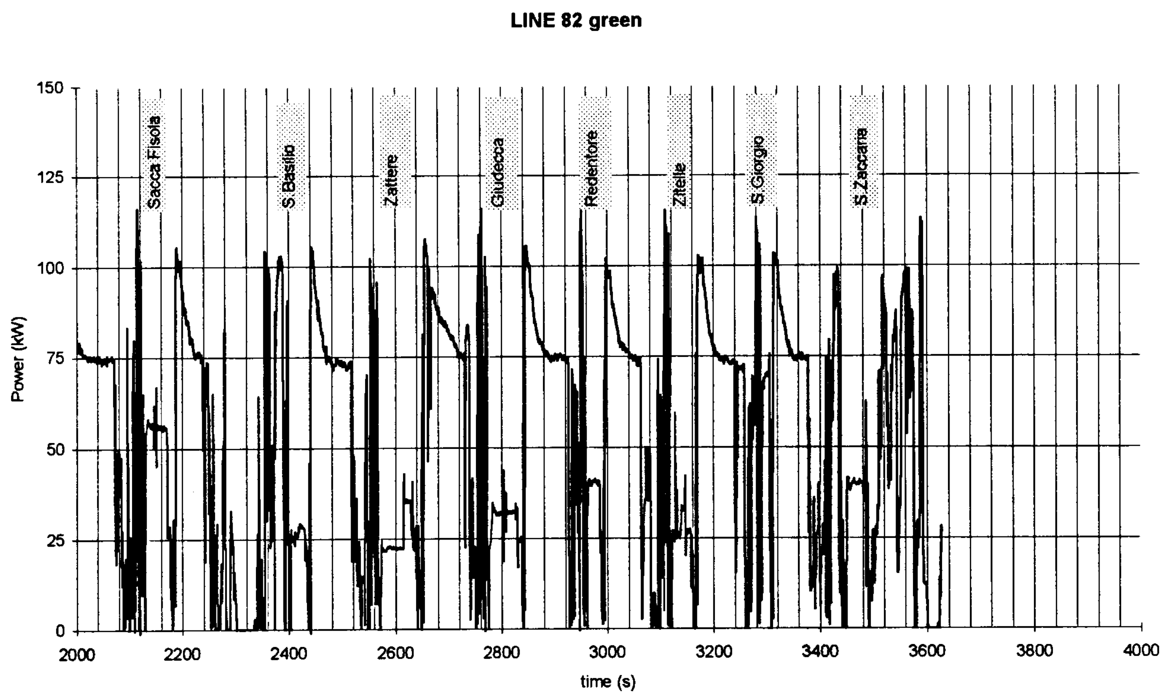

Fig 7 - Recorded propeller shaft power during the second half of the line 82 green course (Sacca Fisola - S. Zaccaria)

PROPELLER SHAFT POWER STATISTICAL ANALYSIS
Absolute Power (kW)

LINE	82 (external)		
FILE	CR78		
MAXIMUM		118.4	
MINIMUM		0.0	
AVERAGE		49.2	
VARIANCY		32.0	
MEDIAN		45.7	
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.107
	5	0.107	0.034
	10	0.141	0.039
	15	0.180	0.037
	20	0.217	0.050
	25	0.267	0.089
	30	0.356	0.090
	35	0.446	0.025
	40	0.471	0.025
	45	0.496	0.019
	50	0.515	0.018
	55	0.533	0.025
	60	0.558	0.019
	65	0.577	0.012
	70	0.589	0.119
	75	0.708	0.116
	80	0.824	0.045
	85	0.869	0.032
	90	0.901	0.027
	95	0.928	0.027
	100	0.955	0.029
	105	0.984	0.013
	110	0.997	0.003
	118	1.000	

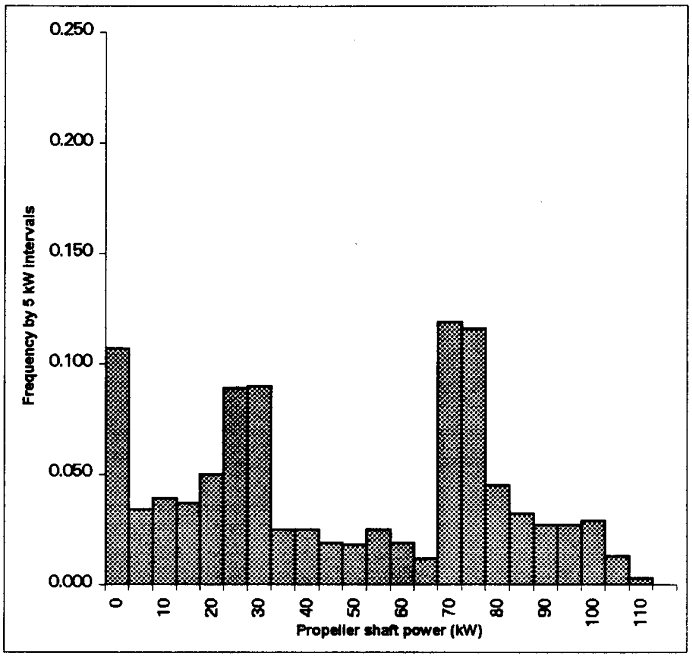

Fig 8 - Power distribution (line 82 green)

The line 82 green (external) operates in the "Canale della Giudecca", outside the main Venice islands, at higher speed and, consequently, requires more power. This causes a relevant shift of power distribution toward the high levels (70 ÷ 90 kW) and a rise of the average used power to about 50 kW.

However, the analysis of these power tracks shows that the displacement (i.e. number of passengers) varies widely (approx. from 40 to 55 t) and this may influence the power profile; moreover, the powering attitude of the vessel's Capt. may influence the power peak pattern and may cause some variation in the mean and maximum rating required for manoeuvring and running.

A general conclusion, however applying to each case, is that *there is a large difference between the mean power used in the operations of the boat and the maximum rating of the engine.*

5 - Analysis of consumption and emissions

The specific consumption trend was identified by analysing several tests carried out on board in steady state conditions at different speeds and without passengers. Collected data underwent a regression analysis whose results are given in figure 9.

In reminding that, especially for routes in the Grand Canal, the load to the engine is about the 20 - 25 % of the maximum rating, figure 9 shows that, in these conditions (even without taking into account the worsening of the consumption due to the very frequent transient states), the fuel consumption may rise very greatly.

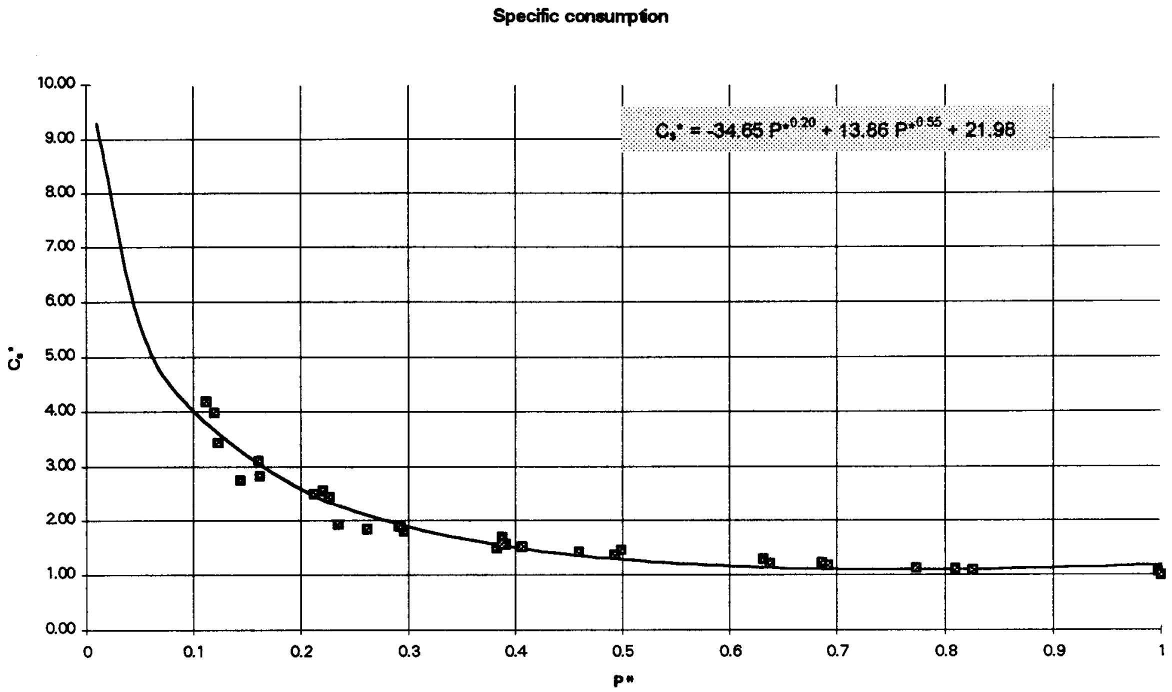

Fig 9 - Consumption data and regression curve

The approach to the emission revelation and analysis was influenced by the difficulties related to the use of portable instruments whose accuracy and reliability are lower than the ones available in standard laboratories. An operation of correlation between the used instruments and more precise ones is carried out in the specialised laboratories of the "Istituto Motori" in Naples. Once reliable coefficients of correction will be found, exhaust data will be corrected, with an improvement of the actual accuracy of the records.

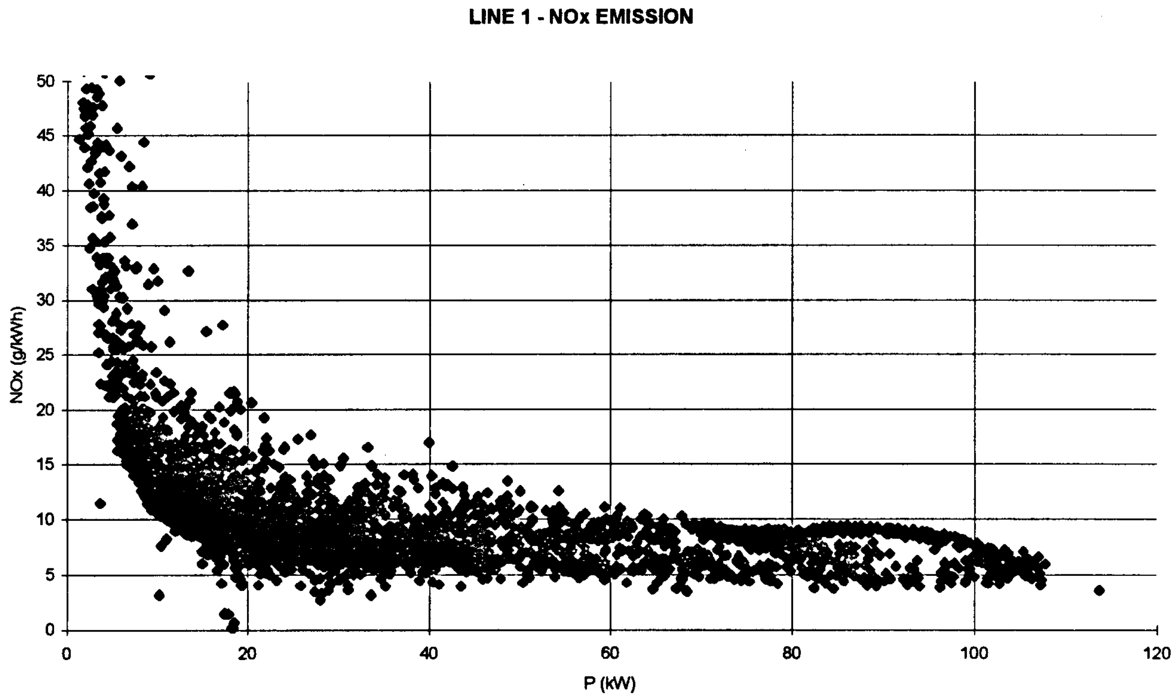

Fig 10 - Scatter diagram of NOx emission vs the absolute power P (line 1)

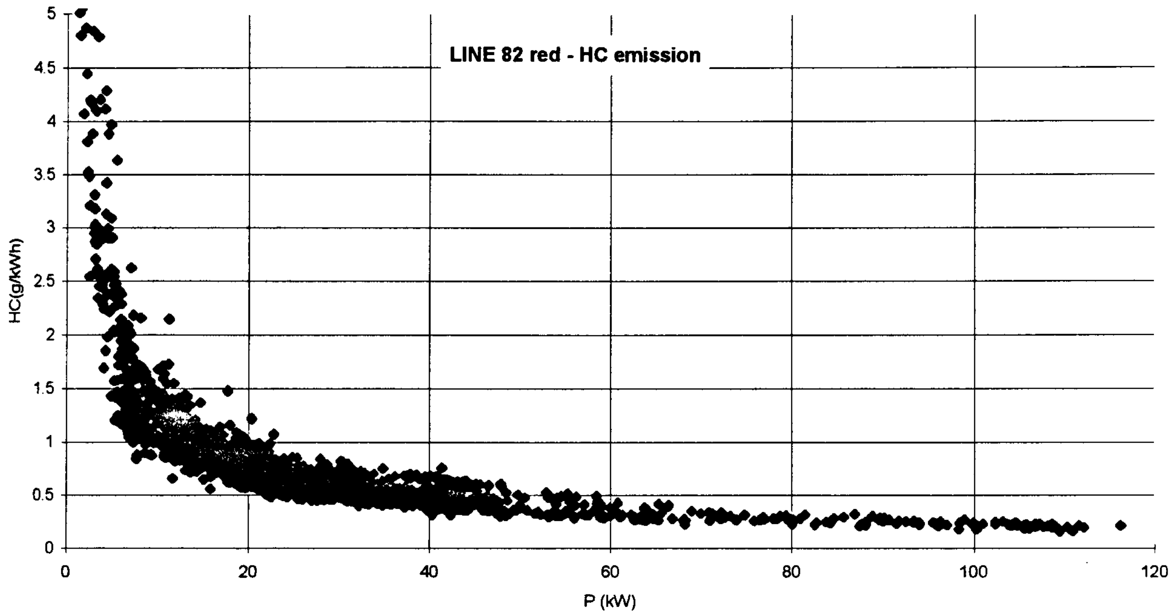

Fig 11 - Scatter diagram of HC emission vs. the absolute power P (line 82 red)

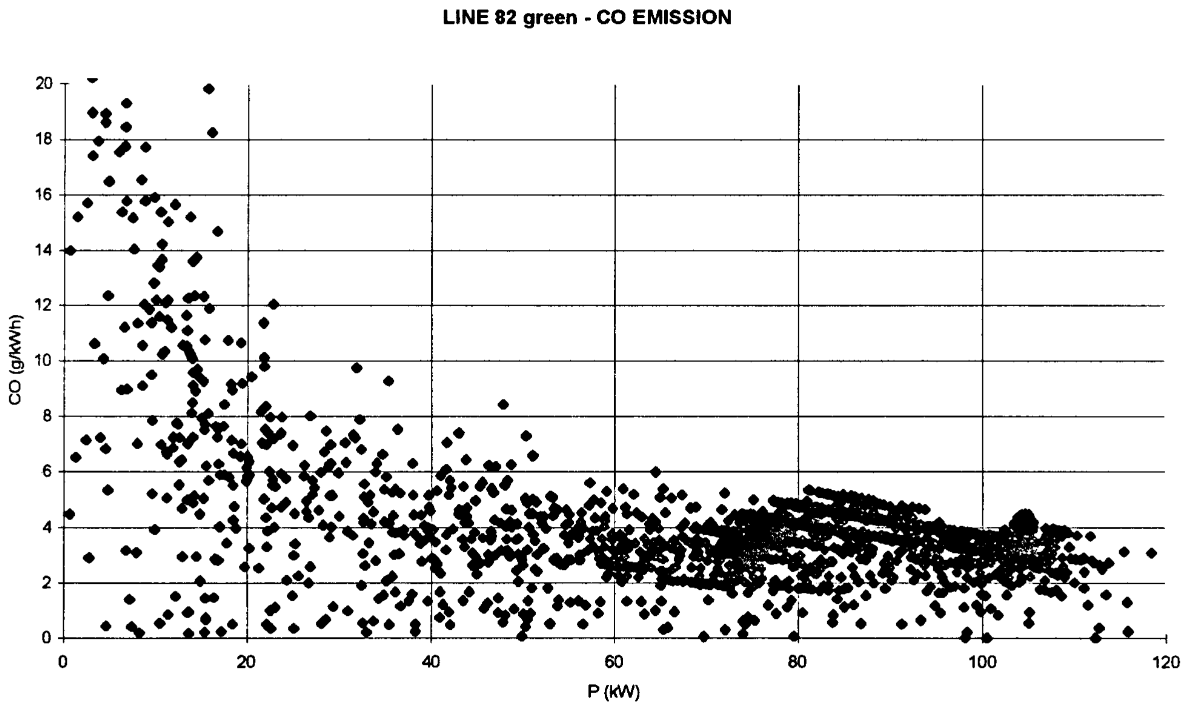

Fig 12 - Scatter diagram of CO emission vs. the absolute power P (line 82 green)

However, it has been established that the present data are underestimated in comparison with the actual ones (15% for NOx , more for the other exhausts).

Up to now, it was not possible to collect data on particulate matter on board. It will be done in the next future.

The emission data were collected in scatter diagrams, for each course, in form of specific emission (in g/kWh) and as a function of the absolute power. Figures 10, 11 and 12 report some of these diagrams showing an acceptable correlation between the pollutant emissions and the power.

In order to give an evaluation of the absolute emission of each pollutant, the mean value of each pollutant read on board, was compared with the current limits valid for I.C.E. destined to road traction. Such comparison was suggested by the fact that in the field of road traction, very different applications (for instance trucks and urban busses) are tested using the same mission profile. On the other hand, the characteristic mission of a vessel working in the Venetian lagoon is closer to the mission of a road bus in city service than the one of a truck; indeed, the irregularity degree of the power demand is very close (both bus and water bus have very frequent transients of stop and go which causes a major demand of low ratings and rarely cover long routes at relatively high speed with a power requirement close to the nominal one).

When the present lack of any standard for the measurement and limitation of pollutant emissions from marine engines will be overcome and specific mission profiles will be set up for each marine application, it is highly probable that the limits reported in the E. C. E. directives for road traction (for instance, 72 306, 88 77, 91 542) will be extended to the marine field, either as they are or even more severe. Thus, it seems reasonable to compare the mean values obtained by the actual mission operation with the limits relevant to I. C. E. under its specific operation profile: the related data are reported in tab 3.

course	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)
line 1	5.97	0.46	8.4
line 82 red	3.84	0.613	8.68
line 82 green	2.8	0.54	9.33
international limits (up to 1/10/95)	**4.5**	**1.1**	**8.0**
international limits (after 1/10/95)	**4.0**	**1.1**	**7.0**

Tab 3 - Mean values of main emissions compared with European limits

Evidently, the tested engine does not respect all the maximum values expected for pollutant emissions although the differences identified are not great (few percents). Even more recent engines, forced to such a load profiles as the ones recorded in this logging campaign, cannot reduce their pollutant emissions at levels much lower than the present ones and this may create some problems in the near future when (probably severe) limits to pollutants will be fixed for the vessels running in coastal and inner waters.

This suggests the conclusion that *it is very unlikely that a remarkable reduction of emissions and fuel consumption can be achieved with propulsion systems following the present working modalities: to cope with future (but not too remote) limits and to obtain a remarkable reduction in emissions and consumption, new energy management systems must be conceived and realised.*

6 - Alternative energy management

The study of the motor boat working pattern suggests the following consideration: *to improve emissions and consumption, in such running conditions, a different philosophy of energy supplying is required*: in particular, it is necessary to uncouple the prime mover from the propeller in order to allow the first to run without following the variations of load, i. e. in better conditions. Naturally, this is possible only by interposing an energy buffer between engine and propeller with the task of compensating, in each step of the course, the difference between the power release and the load.

This is the reason why the *hybrid diesel electric system* was taken into consideration as a good compromise from the technical, economic and environmental point of view.

At present, a project of such an alternative propulsion system is in progress by the above mentioned institutions; possible solutions are compared in order to find the best working conditions from the economical point of view and taking in consideration the need of lowering the pollutant emissions.

In order to give an idea of the trend of this study, several conclusions are reported now about a hybrid diesel - electric system whose layout is given in fig 15.

This system is based on a diesel engine, whose maximum rating is about 70 kW, an electric generator and, in parallel, a battery package and a final (asynchronous A.C. or brushless D.C.) electric motor for the propulsion.

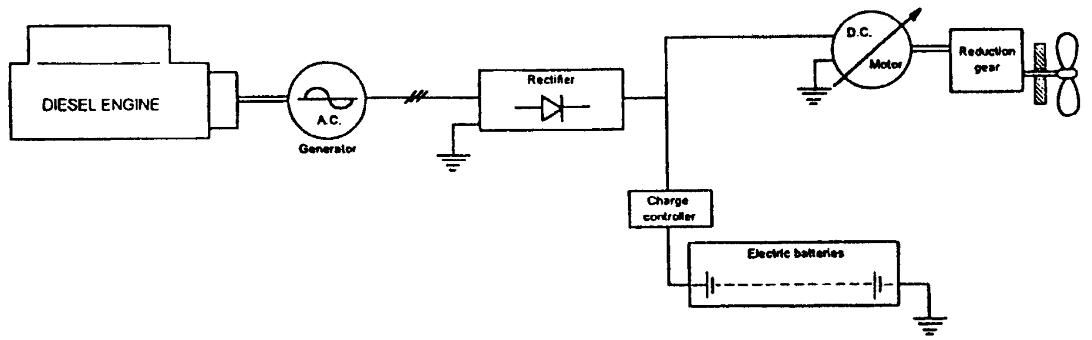

Fig 13 - Scheme of the hybrid diesel - electric system for the water bus working in the Venetian lagoon: layout with D. C. electric engine

The working mode which seems most convenient is between a maximum and a minimum threshold; when the propeller load is lower than the minimum threshold, the diesel engine does not work and the propulsion power is supplied by the battery package (discharge phase). When the power requirement is within the thresholds, the diesel engine supplies both the propeller and the batteries (charge phase); when the load at the propeller overcomes the maximum rating available from the diesel engine, both diesel and batteries supply energy to the propeller (discharge phase). The following table summarises the main characteristics of the system under development.

peak power	120 kW
max continuous rating	70 kW
max torque	2500 Nm
mean power release	21 kW
min batteries energy capacity	5000 kJ (1.4 kW)
charge power	3.5 kW
max power discharge of batteries (1 h)	18 kW
max fast power discharge of batteries (1 min)	50 kW
nominal voltage	240 V
max foreseen mass of the whole system	3400 kg

Tab 4 - Main characteristics of the hybrid system for the Venetian water bus

The hybrid system compares favourably with both the traditional system and the purely electric one: with the former because it makes the engine run within its best operative range, in terms of fuel consumption and exhaust emissions, with the latter because it requires a much lower battery capacity, weight and cost and, lately, a lower primary energy consumption at the power station.

With a system like this, it has been estimated that remarkable reductions of consumption and emissions can be reached; table 5 gives an outlines of the improvements obtainable by means of the hybrid system.

parameter	mean value / value @ max power	percentage variation in comparison with the present system
fuel consumption	1.14	-25 %
NOx emissions	1.05	- 4 %
HC emissions	2.5	- 57 %
CO emissions	1.14	-48 %

Tab 5 - Estimated performances of a water bus propelled by a hybrid diesel - electric system

Conclusions

The need of limiting fuel consumption and pollutant emissions from engines for self - traction applications leads to adopting new energy management philosophies. The particular situation of the public transport in a "town of water" like Venice, claims a new attention in designing the propulsion system of the water busses; indeed, they have to supply the service in the centre of the city directly in contact with people, which can be considered a unique case in the field of navigation.

At the moment, and till electric energy will be easy to store, the hybrid diesel - electric solution with energy reserve, seems the most suited for limiting pollutant emissions and fuel consumption of vessels working in inland waters: indeed, less installed power means less noxious emissions and the peculiar load profile of the hybrid system copes very well with the use of selective catalyst and allows, consequently, remarkable reductions of the overall emissions.

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Bibliography

- F. Balsamo, A. Brighenti, G Landri, A. Paciolla, F. Quaranta "Experimentation and measurements on the propulsion plant of a water bus in service on the'Canal Grande' in Venice" *in Journal of POLISH CIMAC, International Council on combustion engines: Warsaw 23-24/5/1994* Warsaw: CIMAC, 1994 vol. 1, no. 1, pp. 5-17

- F.Balsamo, A. Paciolla, F. Quaranta *Un sistema per la misura a bordo dei parametri caratteristici del funzionamento dell'apparato motore e della navigazione* Napoli : Dipartimento di Ingegneria Navale, maggio 1994

- F. Balsamo *I sensori a bordo delle navi* Napoli: Dipartimento di Ingegneria Navale, maggio 1994.

- F. Balsamo, A. Brighenti, G Landri, A. Paciolla, F. Quaranta *Sistema ibrido per vaporetti: studio di pre-fattibilità* Napoli: Istituto Motori del CNR (paper n. 94RR8222), maggio 1994

- *Recepimento della direttiva 91/441/CEE in materia di emissioni di autoveicoli,* D. M. 28/12/1991, Supplemento ordinario, parte prima G. U. n. 4 7/1/1992, s.g.

- *Nuovi limiti alle emissioni di gas inquinanti prodotti da motori ad accensione spontanea destinati alla propulsione dei veicoli,* D. M. 23/3/1992, Supplemento ordinario, parte prima G. U. n. 77 1/4/1992, n. 63, s.g.