Managing Barge Operations for Improved Productivity

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ABSTRACT

Today the inland waterways industry confronts an environment that is vastly different from that faced by managers even a few years ago. Losses from ongoing operations, common even among the strongest carriers, result from recent precipitous declines in transportation demand and massive overbuilding of most segments of the barge fleet. In this depressed and uncertain setting, traditional rules of thumb concerning productivity-maximizing operating strategies may no longer be appropriate. Some largely theoretical work has been done on determining the principles that will allow operators to maximize productivity and profitability. However, there is little authoritative practical guidance on how to operate based on those principles. Tow operations are completely under the control of vessel pilots, who receive instructions from operations managers but respond primarily to riverine and weather conditions. In this research methods are being devised to bridge the gap between strategic plans and tow operations, the objective being to develop an operations planning system that combines vessel performance data and strategic objectives. The vessel performance data are supplied by an onboard measurement and reporting system. The strategic objectives are based on data from the barge company's management information system. The operations planning system combines these two information sources and uses an onboard microprocessor to develop vessel control parameters that reflect the priorities set by company management.

Today, the inland waterways industry confronts an environment that is vastly different from that faced by managers even a few years ago. Losses from ongoing operations, common even among the strongest carriers, result from a precipitous decline in transportation demand and massive overbuilding of most segments of the barge fleet. Some recent research sponsored by the Maritime Administration (1) charts the history and dimensions of this problem.

It is this depressed and uncertain strategic environment that motivates this research. Traditional rules of thumb concerning profit and productivity-maximizing operating strategies may no longer apply. Yet, even when new strategies can be derived, no effective mechanisms exist to evaluate these strategies and to turn them into guidelines for towboat operations.

The objective of this research is to develop an operations planning and control system that can modify real-time vessel performance to reflect changing strategic objectives. The intent of the system is to promote the operation of tows on the inland waterways so as to maximize corporate productivity and profitability.

IMPROVING PRODUCTIVITY ON THE TOWBOAT

Tow operations are completely under the control of the towboat captain or pilot, and there has been little in the way of guidance to the pilot as to how he should operate in response to the changing circumstances of the towing company. For the most part, the pilot responds to riverine and weather conditions and controls the tow to maintain safety and to achieve whatever speed seems to be appropriate at the moment.

The primary use of the operations planning and control system (OPCS) will be to monitor and control vessel performance based on the testing and evaluation of various operating and strategic options.

Selecting the right set of options is critical today. Some examples of options needing analysis are as follows:

• Current wisdom in the inland waterways industry states, "When business is good you can't go fast enough, and when business is bad you can't go slow enough." Although this operating rule may have wide application, it is highly likely that there are operating speeds between these two extremes that are appropriate for given company circumstances. The OPCS will enable testing of proposed operating speeds and transmittal of appropriate instructions to the towboat pilot.

• There is also some debate within the industry at present as to whether towing companies should make up tows for maximum tonnage or should attempt to improve customer service by adhering to planned and publicized schedules. The OPCS will enable the towing company to analyze the trade-offs involved and then influence towboat operational decisions to enhance company performance.

• Choosing the right match between size of tows and size of towboat for particular river segments and classes of traffic has become problematic as more towing companies find themselves with sufficient towboat capacity to have alternatives readily available. The detailed vessel performance data that will be collected by the OPCS are essential to making the proper choices.

INTEGRATING SHIPBOARD AND SHORE-BASED SYSTEMS

Until recently, there was a decided lack of timely information that could be provided to the pilot for the purpose of improving towing operations. Now, however, Ingram Barge Company and several others are using fuel- and speed-monitoring equipment and other types of vessel performance measurement systems to provide instantaneous feedback to the pilot with

respect to tow operations. Typically these systems provide information on fuel consumption, engine performance, and tow speed. Many barge companies, including Ingram, have also installed a management information system (MIS) so that they have available current information on barges in tow, vessel position, future shipments, and so on. The OPCS will integrate vessel performance and existing management information data to develop towing operations plans. This system will given Ingram the ability to control river operations to conform much more closely to well-defined company objectives and to test and evaluate alternative operating strategies.

The OPCS will also include components that trace the cost and revenue impacts of various operating decisions. Thus, it may be used for cost research, market research, and corporate planning and budgeting.

In the next section the decision-making structure within a barge company is described in overview fashion, focusing on the flow of control from top management all the way through to the company's towboats. This is followed by a description of the data collection system and performance models being developed to implement the OPCS. Preliminary data and prototype analyses with the models are included in this presentation.

BARGE COMPANY DECISION MAKING

Each person within a barge company's decision-making structure is able to exert some control on the company's day-to-day operations. Likewise, each decision maker relies on limited data on vessel and company performance to determine exactly what he should do. Thus, an important first step in this research was to articulate the barge company's decision-making structure. In an earlier paper (2) this topic was discussed in greater depth than can be presented here.

An overview of the typical decision structure is given in Figure 1, which shows the information flows involving the marketing manager, the operations manager, and the vessel pilot. Each of these decision makers responds to a variety of company and external factors. The decisions he makes, in turn, become some of the controls influencing the next decision maker. The performance achieved by the company's tows should be a prime source of feedback influencing future decisions.

The objectives of the barge company for the current period (say, the next quarter) are set with reference to a number of external business factors, such as the state of the economy, world petroleum supply and demand, agricultural production, interest rates, as well as internal factors such as the current budget, profit objectives, capital spending plans, cash flow, and so forth. Developing business to achieve these objectives is the responsibility of the marketing manager. His job involves assessing the markets that the company currently serves or might want to serve in the future and gauging the company's ability to compete effectively. He must then develop price and service packages designed to penetrate those markets to the desired degree.

The service strategies developed and sold by marketing are passed on to the operations department as the service parameters within which they are expected to work. The operations manager is concerned with questions such as which vessels to assign to particular services, how tows should be made up, what schedules should be followed, and all the other details of tow operations. The operations manager must also pay attention to how each individual towing operation fits into the operating pat-
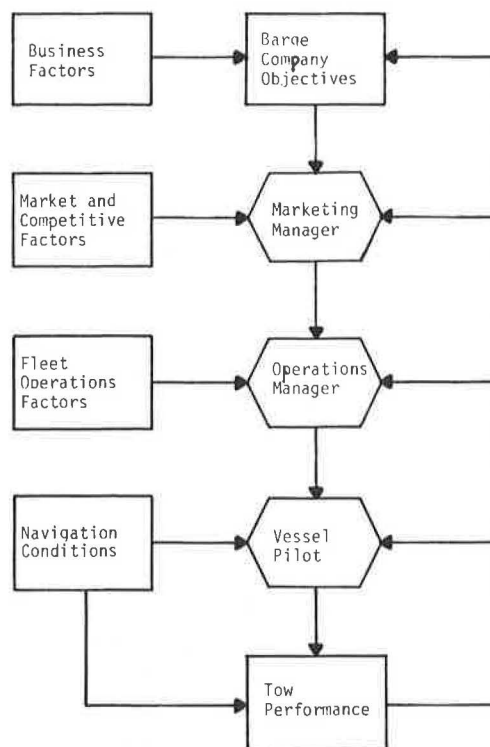

FIGURE 1 Barge company operations management structure.

tern of the entire fleet of towboats and barges under his control.

The towboat captain receives instructions from the operations manager as to which work assignments his tow is to accomplish. Within these instructions, he is generally free to respond to navigation conditions and the performance capabilities of his tow. This research is developing additional information for the vessel pilot so that he can make his operating decisions within the context of the strategic objectives put forth by company management.

The decisions made by the pilot have the most direct impact on the performance of the tow. This performance might be expressed in terms of speed, fuel consumption, the positioning of barges and towboats, and so on. Each of these performance measures has meaning, but perhaps in different ways, to the various decision makers. An onboard system developed to measure certain aspects of tow performance is described in the next section.

MEASURING TOW PERFORMANCE

Ingram has installed a microprocessor-based fuel system, the Pandel FMS-3, on several of its line-haul boats. Figure 2 is a schematic diagram of the system. Its components are located on the main engines, at the head of the tow, and in the pilot house. The system measures fuel flow, engine speed, and tow speed. The central processor makes several simple calculations, the results of which are displayed on a CRT terminal device. The FMS-3 uses an off-the-shelf terminal and printer. The system is software based and most changes are relatively easy to make through the installation of a new program.

System Components

Fuel to and from each engine passes through in-line turbine meters. Fuel temperature is measured at each
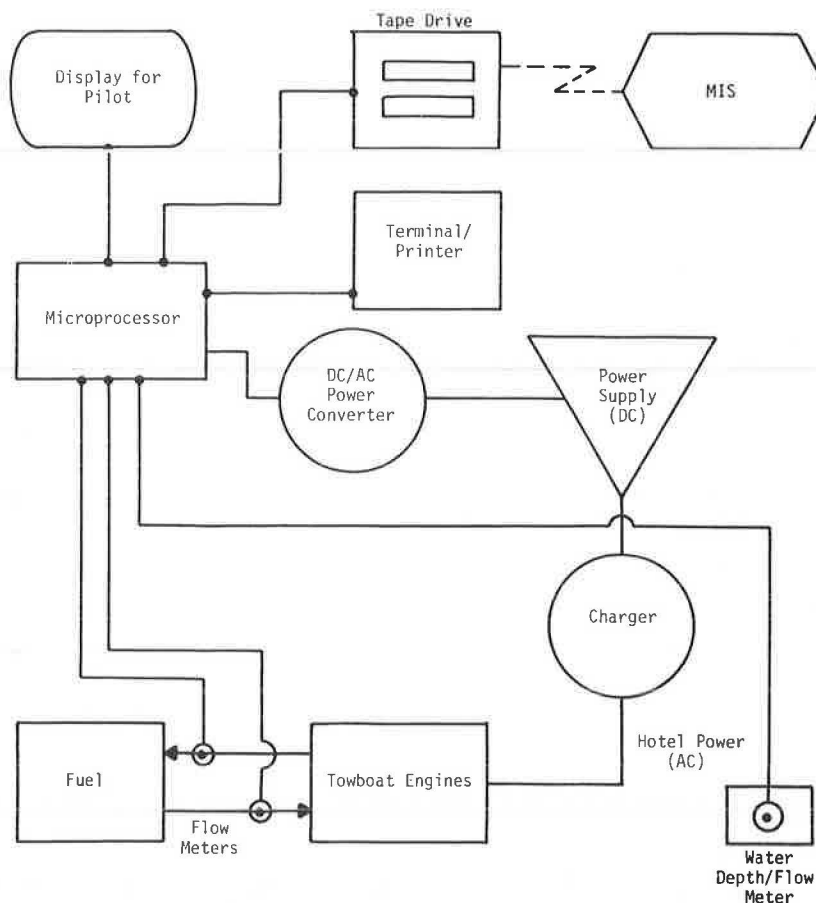
FIGURE 2   Onboard data collection system.

meter. The signals from the meters are conditioned and passed through a junction box and up to the central processor.

Water speed is measured by a paddle wheel mounted on the depth sounder pole at the head of the tow. The signal from the paddle wheel passes to a small radio transmitter. The radio signal is received in the pilot house and passed by cable to the central processor.

Engine speed is measured with electromagnetic tachometers mounted adjacent to the engine fly-wheels. The tach signal passes through the same junction box and up to the central processor.

The microprocessor uses AC power, which is taken from the boat's hotel power and passed through a DC power supply. This step is taken to insulate the electronics from fluctuations and transients in the hotel power.

The central processor displays fuel flow and fuel temperature into and out of each engine, engine speed, and tow speed through the water. It calculates net fuel flow for each engine and for the boat. It also calculates fuel efficiency for the boat and keeps track of the aggregate fuel consumed by each engine.

Ingram's MIS is housed in a Hewlett Packard (HP) 3000 Model 68 computer and provides compatibility with HP 150 microcomputers available to the management team. Communication between the FMS-3 and the Ingram MIS is handled with microcassette tapes and a high-speed (9,600-baud) tape recorder and player. The recorder attains its high speed via a buffer. The data are transmitted in binary form, utilizing neither stop bits nor control codes.

The data are collected by the FMS-3 and recorded on a cassette tape. The tape is sent to Nashville and read by a second high-speed recorder-player, which puts the data onto a flexible microdisk for the HP 150. A BASIC program will read and sort the data and create a master file that will be transferred to the HP 3000 for safe storage. As each file is needed for analysis it will be called back to the HP 150. Results will be filed, transferred, and stored in the HP 3000.

Use of the System

The pilot can input his own estimates of ground speed, water speed, or current. He can also compute ground speed over a measured course and automatically enter that into the processor. The system will automatically utilize the most recently input speed information regardless of the source. If the water speed device is working properly and if the pilot makes frequent ground speed measurements, the speed and fuel efficiency data displayed by the system should be accurate.

The FMS-3 provides the pilot with a real-time measurement of fuel flow and speed. With it he can instantly see the effects of any changes in the way that the boat is operated. If something such as water depth, current, engine speed, or a host of other factors changes, the efficiency of the boat will also change. The direction and extent of the change are automatically displayed on the screen.

The FMS-3 is installed on Ingram boats to function primarily as a tool for the conscientious pilot. It is understood that he already navigates the tow along the path of least resistance. He would

do this with or without a fuel measurement computer on board. His training and experience have taught him how to maneuver the tow. With the engines set to run at full power, the path of least resistance is also the path of maximum speed. The pilot knows and seeks out this path whether or not he is running at full speed. Without the computer, however, he does not know what the effect of engine speed is on fuel efficiency. The FMS-3 provides information on efficiency. Its intended use is to help the pilot to find the best speed at which to run his boat's engines.

Illustrative Measurements

Operating data were gathered under controlled conditions from an Ingram towboat. Water speed, ground speed, and fuel flow were measured with the FMS-3 and recorded manually. Data were collected for four different tow configurations: light boat, 2 empties (2 wide x 1 long), 5 empties (2 wide x 3 and 2 long), and 15 empties (3 wide x 5 long). The boat ran up-river from Baton Rouge while the data were collected. The data relating fuel consumption and engine speed are presented in Figure 3. The data support the common assumption that the relationship between fuel use (gallons per mile through the water) and engine speed is convex with respect to the origin. Heavier tows consumed more fuel. Also, the data points for two empties and five empties were nearly identical, leading to the conclusion that the cross-sectional area of the tow front is a very significant operating variable.

In the OPCS, data from the FMS-3 will be used to calibrate and implement various tow performance models. These are taken up in the next section.

TOW PERFORMANCE MODELS

Strategic control of vessel operations requires analysis of the relationships between performance measures and control parameters. The relationships will appear in the OPCS as a set of control process models, including a tow performance model, average and marginal tow cost models, and a revenue-profit model.

Generic Relationships

One output of the system will be guidelines for the towboat pilot concerning what speed he should try to attain in given circumstances. Thus much of the modeling interest centers on the relationships between various measures of tow performance and speed. Figure 4 presents a generalized analytical framework for dealing with these relationships.

The precipitous rise in fuel prices a few years ago engendered considerable interest in towboat fuel consumption characteristics. The lowermost curve in Figure 4 illustrates the general relationship between fuel consumption (and hence fuel cost) and tow speed, which was verified by the data presented earlier. At very low speeds fuel efficiency is relatively poor. The tow then moves into a more favorable operating regime, and the point of minimum fuel cost (S_f) is reached. As speed increases beyond this point fuel consumption increases rapidly, because tow resistance tends to increase with the square of tow speed.

The point of minimum fuel cost may not be the point of minimum average total cost, because there are other cost elements to consider. Average fixed cost per hour declines as tow speed increases, be-
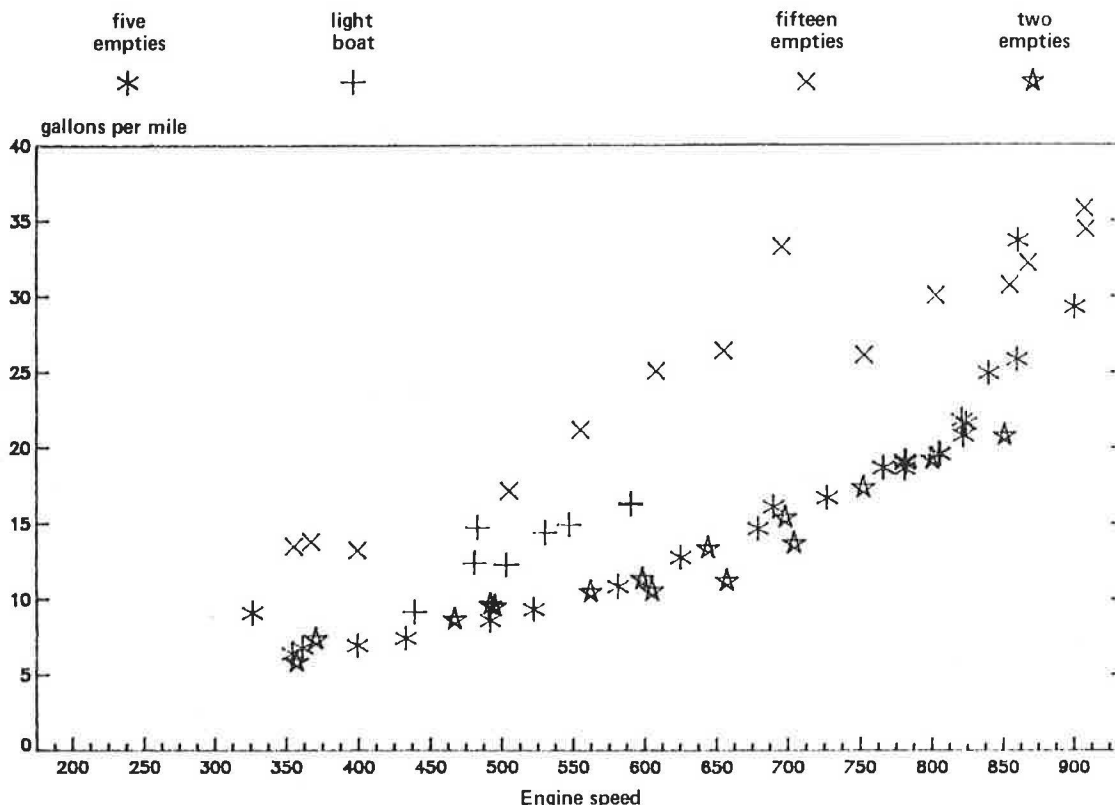

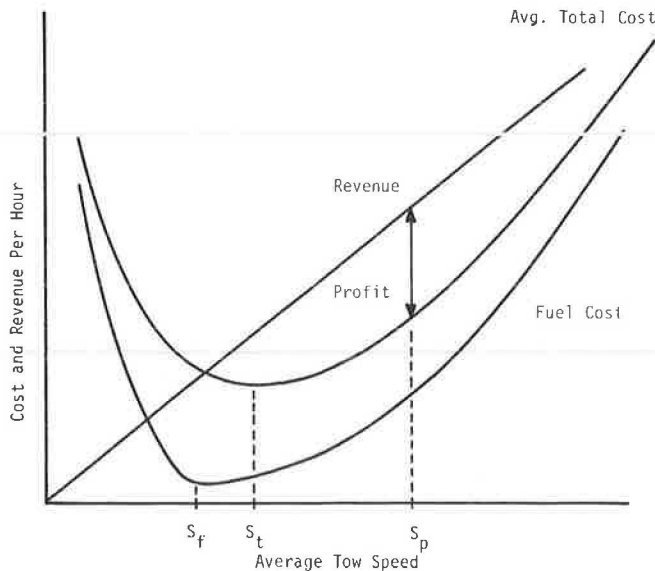
FIGURE 3   Tow operating data.

FIGURE 4 Generalized towing profitability model.

cause the fixed elements of cost are spread over a
greater number of hours. Average variable cost
starts at zero when tow speed is zero, because by
definition there is no cost when no output is being
produced. As tow speed increases, output increases
and variable cost becomes positive. At the higher
speeds, labor, material, and equipment all incur
added stress and wear, so average variable cost
tends to increase. Thus the sum of the two, the
average total cost curve, tends to be U-shaped as
shown in Figure 4. The low point on it occurs at
speed S_t, which tends to be higher than S_f.

A third curve, the revenue curve, must be intro-
duced to find the speed that will yield maximum
profit. One possible revenue curve is shown in Fig-
ure 4. No revenue can be earned if the tow is not
moving at all, so this curve passes through the
origin. As higher speeds are attained, the revenue
accrued per time unit increases. The speed that
yields maximum profit (S_p) is found at the point
at which the distance between the revenue curve and
the average total cost curve is at its maximum. For
the case shown in Figure 4, this speed is higher
than both the minimum cost and minimum fuel cost
speeds.

The cost and revenue curves can shift while the
boat is under way because of changes in crew size,
fuel price, barge fleeting and positioning require-
ments, weather, river stage, outside charter re-
quirements or opportunities, and a host of other
factors. The optimum tow operating speed will change
as these other factors change.

Tow Speed Equations

A number of tow speed equations developed by pre-
vious researchers were reviewed, and four were
selected for possible use in the OPCS. The Howe
model (3,pp.23-33) and the Toutant model (4) are
basically the same equations, the latter being a
simplification of the former. Both equations require
tow and river dimensions in order to determine speed
developed at a given horsepower applied. The Toutant
model also provides speed determination for both
open-wheel and Kort nozzle boats, and utilizes a
factor to adjust for the differences in tow resis-
tance produced by various tow configurations (inte-
grated, mixed, etc.).

The tow speed equation developed for the Inland
Navigation Systems Analysis (INSA) program (5) was
also considered. This equation requires the use of
various hard-to-obtain parameters: user-specified
coefficients relating to direction, a fastening
coefficient relating to barge configuration, and the
barge specific resistance.

The fourth model considered was a speed equation
developed at Pennsylvania State University (6) using
regression analysis. This equation determines tow
speed as a function of horsepower, river current
speed, direction of travel, and number of loaded and
empty barges. Sample calculations were made using 15
loaded and 15 empty barges with 0 and 4 mph river
current. The difference between loaded and empty
tows was about 3 mph. The difference between up-
stream and downstream travel was about 3 to 4 mph
depending on river current.

All of the equations considered are given else-
where (7). The Howe and Toutant models were rejected
for the initial OPCS tow performance model because
of their reliance on river parameters, which would
vary over time and distance and thus be difficult to
use for operational purposes. The INSA model was re-
jected because of the need to compute fastening
coefficients and specific barge resistance for each
tow.

The final selection was the regression equation,
displayed in the following as Equation 4, which was
chosen for its simplicity. For this use, however, it
will have to be recalibrated. The coefficient of the
river speed term (0.1475C) appears to be too small
in light of the actual data presented. It also
appears that a variable related to the tow cross
section will have to be added. If calibration of a
revised regression equation produces unsatisfactory
results, a revised Toutant equation (without river
param- eters) will be experimented with.

Comparison with Measured Tow Speeds

Tow speeds estimated with the Penn State and Toutant
equations were compared with data collected on board
two instrumented vessels during break-in and initial
use of the system. The data used were those tow runs
where sufficient information was available and be-
lievable. Data were not used if the run contained
delays. Only through runs were considered. Two basic
assumptions were made: (a) that time and mile marker
data input by the pilot were accurate, and (b) that
speed and fuel consumption from one observation to
the next were constant.

Three calculations were made with the trip data.
Average ground speed was determined by subtracting
beginning and ending mile points and dividing by
total elapsed time. Fuel consumption for the trip
was the sum of the consumption for each leg. Divid-
ing by the total trip time gives average fuel con-
sumption for the whole trip in gallons per hour. A
gallon-per-mile figure was obtained by dividing
gallons per hour by miles per hour. The regression
equation for speed was used to estimate tow speed
with river current (C) assumed to be zero.

Data for 10 trips with two different towboats are
summarized in Table 1. The range of rpm values is
listed for reference. The data in Table 1 show that
actual average ground speeds are about 3 to 5 mph
different from the calculated speed. If the factor
0.1475C is used, the required river current speed to
make the equation work would be 20 to 30 mph in some
cases. Obviously, the coefficient 0.1475 is too low,
or other model parameters are incorrect. In fact,
the regression equation was estimated with data for
smaller tows operating on locking rivers, so new
parameters are needed for Lower Mississippi River
conditions.

TABLE 1 Tow Performance Data from Onboard System

Parameter	Trip No.									
	1	2	3	4	5	6	7	8	9	10
Direction	Up	Up	Up	Up	Down	Down	Down	Down	Up	Up
Loaded barges (no.)	3	0	5	5	29	35	30	30	4	4
Empty barges (no.)	37	49	44	44	0	0	0	0	25	31
Mileage	380	436	227	121	91	178	147	192	107	252
Speed (mph)	4.36	4.54	4.41	3.84	9.25	9.75	11.31	11.46	5.35	4.78
Fuel consumption										
Gal/hr	441.81	450.68	464.92	576.82	147.97	136.38	242.54	365.40	398.62	359.75
Gal/mile	101.33	99.27	105.42	150.21	15.99	13.99	21.44	31.88	74.51	75.31
S(calc) (mph)	9.77	9.99	8.98	8.98	8.87	7.38	7.37	7.37	8.79	8.53
S (Toutant)	8.7	6.7	6.7	6.7	10.3	8.9	7.9	7.9	8.9	7.7
Power range (rpm)	855-906	879-908	842-906	832-906	600-630	625-646	722-892	843-886	882-910	846-906

Note: S(calc) = speed calculated from Equation 4, with river current assumed to be zero. S (Toutant) = speed calculated with Toutant equation (channel width = 400 ft, depth = 30 ft, current speed = 0).

The calculations made using the Toutant equation assumed generous channel dimensions (width = 400 ft, depth = 30 ft). In general, these tow speeds were lower than the regression equation speeds for upstream tows and slightly higher for downstream tows. These figures are shown in Table 1. Note that the implicit current speeds are quite reasonable for most cases.

Tow Performance Model

The basic equation used in this model is Equation 1, given as follows: profit equals revenue minus cost. In towing operations, all costs for a given trip are considered to be fixed except fuel costs, so the equations show fuel and fixed costs separately.

$$P = R - E - F \tag{1}$$

$$R = (\sum_i r_i C_i)/T \tag{2}$$

$$E = e(60 \sum_j q_j t_j)/T \tag{3}$$

$$S = 7.348 - 3.93 (A) + 0.0915 (H)^{1/2}$$
$$- 0.04288 (5.67 B_1 + B_e) \pm 0.1475C \tag{4}$$

$$q_j = 3.54 \exp[(0.00427) (rpm)] \tag{5}$$

where

P = profit ($/hr);
R = revenue ($/hr);
E = fuel costs ($/hr);
F = fixed costs ($/hr), to be obtained from the MIS;
r_i = revenue rate ($/ton) for barge i;
C_i = capacity of barge i (tons);
T = total trip time (hr);
e = cost of fuel ($/gal);
q_j = fuel consumption rate for operation j (gal/min);
t_j = time of operation j (hr);
S = calculated ground speed (mph);
A = direction of travel (1 upstream, 0 downstream);
H = horsepower of towboat (hp);
B_1 = number of loaded barges;
B_e = number of empty barges;
C = river current speed (mph); and
rpm = engine speed.

Revenue for a given tow movement is the sum of the freight rate (r_i) times the capacity (C_i) for each barge in the tow. Dividing by total trip time (T) gives trip revenue in dollars per hour.

The cost of fuel (e) and the fixed costs relating to each tow movement will be available from accounting data. Provision should also be made for onboard input of any additional costs incurred while en route.

For an accurate tally of fuel consumption, the pilot should be encouraged to take a reading of time, mile point, and fuel consumption each time the tow speed is changed and each time any major activity change occurs, for example, waiting at idle, making or dropping tow, locking. The total fuel cost then would be the sum of consumption at each activity times fuel price per gallon.

Example

As an example of use of the model, take the case of a tow moving 29 loaded barges 91 miles downstream (trip 5 in Table 1). The actual speed was 9.25 mph. From the regression equation, speed was calculated to be 8.87 mph, indicating a river current of 2.58 mph. Fuel consumption was 147.97 gal/hr or 15.99 gal/mile. Now six loaded barges are added and two conditions are considered.

Condition 1

Maintain the same engine power (rpm) as in the original case. From the regression equation the new speed for the added load is 7.38 mph. Using the same river current, the actual speed would be 7.76 mph (approximately 1.5 mph slower). The 91-mile trip at this speed would take 11.72 hr or 1.89 hr longer (1 hr 53 min). Because engines are running at the same speed, the fuel consumption rate will be as before, 147.97 gal/hr, but for the additional time period. Total fuel consumption for the trip will be increased by 279.17 gal. The revenue will increase according to the rate and capacity of the added barges ($\sum r_i C_i$); fuel costs will increase by $279.17 (at $1/gal). Total fixed costs would also increase because of the extra 2 hr afloat.

Condition 2

Maintain the original tow speed of 9.25 mph. To do this, engines must be run at a higher power. In the original case, the engines were run at 600 to 630 rpm. The equation for fuel consumption in terms of power yields 617 rpm for the consumption rate of 147.97 of the original case. Although we have no relationship at this time between speed and power,

assume that a new engine speed of 650 rpm is used to maintain the 9.25 mph. Fuel consumption rate then would be 170.42 gal/hr or 18.42 gal/mile. This is an increase of 2.43 gal/mile and a total increase in fuel of 220.68 gal. Again, revenue would be increased and fuel costs will increase, but total fixed costs would remain the same as in the original case.

SUMMARY

The objective of this project is to make the MIS and the onboard microprocessor work together to improve operations planning and control. The system implements through hardware, software, and training the conceptual and organizational structures previously presented. Corporate information sources, planning and operational control decisions, and tow performance results are integrated in real time to achieve improved towing operations.

Measurement of project benefits is an important and integral part of this entire research effort. A principal research hypothesis underlying this project is that the absence of towboat performance measures prevents cost-effective vessel control. Providing such measurement is a first step in this research effort. The measured changes in capital, labor, and fuel productivity will be used to judge the impact of the project on corporate profitability.

The authors believe that the potential economic benefits of the project are substantial, but one of the objectives of this research is to make this determination. For example, use of the OPCS should result in a more cost-effective trade-off between fuel and other operating expenses. Ingram alone spends nearly $15 million each year on fuel, so even modest percentage reductions in fuel consumption are highly leveraged.

ACKNOWLEDGMENTS

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