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SAFETY BENEFITS OF DIGITAL NAVIGATION

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1. INTRODUCTION

Every day, more than one hundred tank ships and thousands of other vessels make their way into and out of the United States' ports and harbours. The cargo and passengers carried by these ships are important to the U.S. economy. Half of the nation's petroleum consumption and more than 90 percent (by weight) of its foreign trade is carried in ships.

Accidents of various kinds happen to these ships with some frequency. We are interested here in navigational accidents -- groundings, collisions, and rammings -- which constitute a large portion of commercial maritime casualties in U.S. waters and result in losses of several billion dollars each year. In particular, we focus on the expected safety benefit and cost of new technologies, such as electronic charts and integrated navigation systems (EC/INS), which can help reduce these losses by preventing accidents.

2. ADDRESSING LOSSES IN COMMERCIAL SHIPPING

The main purpose of electronic charts and integrated navigation systems is to improve the safety of navigation, and thereby to reduce the cost, both to shipping firms and to society as a whole, associated with casualties in commercial shipping. Electronic charts (EC) are computer-based systems that are expected to replace traditional paper charts as the basis of navigation in the future (KITE-POWELL and GAINES, 1995a and 1995b). Integrated navigation systems (INS), also called integrated bridge systems, are vessel control stations that integrate and (partially) automate all navigation functions and tools (position fixing, route monitoring, radar, autopilot, engine and rudder controls, etc.) in a single location, allowing a small number of operators to perform all tasks necessary for safe navigation efficiently and

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effectively. INS generally use an electronic chart display as a focal point for the display of much of the relevant information.

In designing or updating a ship's navigation system, it is possible to choose from a continuum of options from simple, stand-alone EC devices to completely integrated "cockpit-style" one-person INS stations. The effectiveness of these systems in preventing navigational accidents depends on both system design and training of operators. Little hard data on the effectiveness of specific systems has been published to date. In this paper, we consider a generic technology of this kind, which we refer to as "EC/INS", and its potential to help reduce losses from maritime casualties.

Electronic charts and integrated navigation systems are one possible approach to the problem of losses due to navigational accidents. Alternative (or complementary) technological approaches with some of the same benefits include vessel traffic service (VTS) systems and double hulls. VTS systems monitor the movements of all vessels in an area from a central station and advise them of impending navigational problems (MAIO *et al.*, 1991). Double hulls are a design feature in which a second watertight hull is built into a vessel at some distance from the outer hull, providing a measure of protection in the event of an accident (NRC, 1991).

Our focus in this paper is on the safety benefits of EC/INS, quantified as avoided casualty losses. There are other benefits associated with this technology, notably improved efficiency of navigation. In practice, some of the benefits of EC/INS are likely to be realized as efficiency gains, while another part will manifest itself as improvements in safety (JIN *et al.*, 1994). We believe that our focus on safety leads to a conservative estimate of the total social benefits of modern maritime navigation systems.

3. A MODEL OF MARITIME CASUALTY LOSSES AND SAFETY BENEFITS

We have developed and implemented a simple model of the safety-enhancing benefits (avoided losses) that may be expected from the adoption of certain technologies. Our implementation of the model is specific to casualties addressable by EC/INS ("EC addressable casualties"), but is easily extended to others. It draws heavily on the modeling efforts performed in support of the U.S. Coast Guard's Port Needs Study (PNS).

We designate as L_0 the present value of total expected losses from maritime casualties for a fixed future period, assuming no safety-enhancing technological change. L_0 represents the baseline expected loss against which technological options can be judged.

The benefit of adopting technological option(s) (designated as scenario i) over the future period is the avoided loss: $B_i = L_0 - L_i$. The net benefit of implementing scenario i is $B_i - C_i$, where C_i is the incremental cost, in present terms, of the technology over the future period. The benefit/cost ratio of policy option i is B_i/C_i.

To implement this model, we used historical casualty data for 1981-90 from the U.S. Coast Guard's CASMAIN database. Most other data, such as transits and losses, come from PNS. Our future period extends from 1996 to 2010, and we discount future benefits and costs to 1995 dollar terms.

The number of historical and expected future transits is calculated from PNS data, which suggest that the average annual number of transits will be between 10 and 40 percent greater, depending on the type and size of vessel, in the future period (1996-2010) than it was during the 1980s. Our estimates of average total losses per casualty are also based on data from PNS. The PNS study included in its loss estimation a large range of damages, ranging from loss of human life and personal injuries to vessel hull damage, cargo losses, spill clean up costs, losses in tourism and recreation, losses in commercial fish species, impacts on marine birds and mammals, and bridge and navigational aids damage. Table 1 shows our estimate of average unit losses for all U.S. waters.

Table 1

Total loss per casualty, $1000 (1995), averaged over all U.S. waters

	average total cost, $1000		
	grounding	collision	ramming
passenger vessel			
medium	1470	1810	1590
small	670	950	920
dry cargo vessel			
large	330	1510	1920
medium	320	1580	2010
small	660	740	730
tanker			
large	4030	8900	8610
medium	720	2250	1930
small	240	820	500
dry cargo barge			
large	20	120	70
small	20	70	150
tank barge			
large	6880	11,550	10,490
small	670	5390	4900
tug/tow			
small	70	70	140

Perhaps the most volatile element in the PNS loss estimation procedure is the model used to calculate natural resource damages. These damages -- loss of fish, birds, marine plants, and other species -- account for between 10 and 40 percent of total damages, depending on the location and nature of the accident. The PNS results are based on a version of the Department of the Interior's Natural Resource Damage Assessment Model for Coastal and Marine Environments NRDAM/CME which is in the process of being replaced by a new version of NRDAM/CME (Federal Register 59(5):1062-1189). Our preliminary analysis of the new model's parameters suggests that there is no consistent way to scale results from the previous version to reflect the likely new model results. We therefore present our results here with the caveat that they include natural resource damage estimates based on an "old" version of the NRDAM/CME.

4. SAFETY BENEFITS OF EC/INS

The accidents that may be avoided by using EC/INS primarily include groundings, collisions and rammings. However, not every such casualty can be prevented by the use of an electronic chart. For example, ships sometimes run aground because they lose power or because of a rudder failure; EC/INS is of little help in these situations. We are interested here in those casualties caused by navigational error or human inattentiveness. These are defined as potentially addressable by the use of EC/INS, or "EC addressable".

We identify such casualties by the "cause of accident" coding in the Coast Guard's CASMAIN data. Table 2 summarizes ten-year counts of EC addressable accidents in U.S. waters.

Table 2

Casualty counts from CASMAIN database, 1981-90. Includes tankers, dry cargo ships, passenger ships, barges, and tug-towboats.

	all causes	EC addressable
grounding	7217	2414
collision	2817	1165
ramming	4004	1609

Casualty counts and transits together can be used to compute casualty rates. Table 3 shows the historical rate (1981-90) of EC addressable casualties in U.S. waters. We assume that these rates remain constant for the future study period (1996-2010) in the absence of technological change.

Table 3

Number of casualties, per 100,000 transits, potentially addressable by EC/INS, U.S. waters, 1981-90

	EC addressable casualties per 100,000 transits		
	grounding	collision	ramming
passenger vessel			
medium	39.29	7.86	62.87
small	0.94	0.36	0.39
dry cargo vessel			
large	18.50	8.38	15.50
medium	2.35	0.47	2.69
small	0.29	0.25	0.30
tanker			
large	39.30	12.98	18.17
medium	3.43	2.29	4.19
small	7.25	4.53	7.25
dry cargo barge			
large	63.47	63.47	43.43
small	18.49	11.27	17.81
tank barge			
large	101.94	34.87	57.68
small	24.45	11.57	12.25
tug/tow			
small	21.03	9.60	13.51

Our analysis suggests that we can expect over 24,000 groundings, collisions and rammings involving commercial vessels in U.S. waters between 1996 and 2010 in the absence of technological changes -- on average, between four and five accidents each day. Most of these will be relatively harmless, but some may have severe consequences. Average expected losses associated with these casualties in the next 15 years will be more than $2 billion per year, or more than $6 million per day (1995 dollars). Of these expected casualties, nearly 9000 (more than one third) are potentially addressable by EC/INS.

Not every casualty that is addressable by the use of EC/INS will in fact be prevented if the technology is adopted. Operational experience with EC/INS accumulated and analyzed to date is not sufficient to assign effectiveness factors to specific vessels classes. We consider it likely that EC systems, properly used, can achieve an effectiveness of 50 percent for groundings and 25 percent for collisions and rammings (50/25/25). EC systems are most effective in preventing groundings, since they automate the plotting of the vessel's position and can warn the mariner of shallow water in the vessel's path. While electronic charts alone may increase the margin of safety with respect to collisions and rammings as well, this effect is likely to be less pronounced than with groundings. Full INS can potentially achieve even higher levels of effectiveness. Table 4 shows expected benefits (avoided losses; $B_i = L_0 - L_i$) for three representative levels of effectiveness.

Table 4

Expected EC/INS benefits (avoided losses, B_i), 1996-2010, in 1995 dollars, 10% real discount rate, for various effectiveness factors (e_i)

	pessimistic		optimistic ("INS")		likely ("EC")	
	e_i(%)	B_i($M)	e_i(%)	B_i($M)	e_i(%)	B_i($M)
groundings	25	410	75	1580	50	800
collisions	10	250	50	1240	25	630
rammings	10	260	60	1200	25	660
total avoided losses		920		4020		2090

These benefits are unevenly distributed over vessel classes. Ships and barges carrying hazardous liquid cargoes, such as crude oil and refined petroleum products, account for more than 80 percent of the expected benefits. These results suggest that the use of EC/INS on tank vessels ought to be given priority.

Similarly, the expected benefits from the use of EC/INS are distributed unequally among geographic regions. The Gulf of Mexico accounts for more than half of all expected benefits, and the region centered around New York accounts for an additional 13 percent. This may have implications for the prioritization of areas in the production of digital chart databases.

These breakdowns reflect in part what one observer of the maritime industry calls the United States' "big problem with small barges in the Gulf of Mexico". The peculiar circumstances of large convoys of barges, pushed or pulled by relatively small tugs, operating with small crews in confined waterways, and outside the scope of many safety regulations governing self-propelled cargo vessels, lead us to be cautious about how effective EC/INS by themselves can be in reducing the casualty rate for small barges.

5. COMPARISONS AND COMBINED EFFECTS OF ALTERNATIVES

It is instructive to compare the level of safety benefits that may be achieved by the use of EC/INS to those achieved by alternative (or complementary) technologies, such as VTS and double hulls. By estimating also the cost of each technology, we can compare alternative policies (combinations of technologies) in terms of their expected benefits and costs. We first consider each technology in isolation.

The costs and benefits of double hulls have been examined at length by NRC (1991). Double hulls are expected to reduce cargo outflow in the event of an accident on average by 40 percent in small tankers and by 70 percent in large vessels. With an average total accidental spill volume of 9 000 tons per year for all U.S. waters and a cost of cleanup and remediation (at the high end) of $68,000 per ton spilled, double hulls can be expected to prevent some $370 million (1995 dollars) in oil pollution damage annually. The incremental cost of double hulls (operating and prorated construction cost increases) has been estimated to range from about $1 million per year for a 40,000 dwt vessel to about $2.5 million per year for a 240,000 dwt tanker. For the approximately 1000 tank vessels operating in U.S. waters, this implies an annual cost on the order of $1.6 billion (1995 dollars). In the Alaska-(U.S. West Coast trade, which is dominated by large vessels, JIN *et al.* (1994) have found that the cost of double hulls is approximately equal to their pollution-reducing benefits. When all oil transport is considered, the large number of smaller vessels drives up total costs and leads to negative expected net benefits (scenario 7, Table 5).

The benefits and costs of VTS are examined in detail in the Port Needs Study. This study estimated a net benefit of $840 million (adjusted to 1995 dollars) from improved VTS installations in all 23 PNS study zones (1996 to 2010), with an associated cost of $340 million (scenario 4, Table 5). Benefits of $770 million may be realized from improved VTS installations in eleven U.S. ports for which PNS estimated positive net VTS benefits the cost of these installations was estimated at $190 million (1995 dollars) (scenario 6, Table 5).

The cost of implementing EC/INS includes the installation of such systems on vessels as well as the production and maintenance of the necessary databases. To achieve the full benefit of $2.1 billion over the study period ("50/25/25" scenario, Table 7), some 10,000 vessels trading in U.S. waters must be equipped with EC systems, and digital charts must be prepared and maintained for all U.S. waters. We estimate the cost, in present value terms, of commercial stand-alone EC systems at $50,000 per vessel, and the cost of producing and maintaining digital data at $150 million, for a total estimated cost of about $750 million (scenario, 1, Table 5). Note that if EC systems achieve effectiveness only at the "pessimistic" level (scenario 7, Table 5), the benefit/cost ratio is close to one, suggesting that it may be difficult to justify requiring electronic chart systems of this effectiveness (25/10/10) on all commercial vessels (scenario 2, Table 5).

As we discussed in the previous section, the greatest benefit is likely to be realized from EC/INS by focusing first on large tankers and tug/tows handling large tank barges, and on the most accident-prone regions of operation. Approximately 1000 such vessels operate in U.S. waters; and together, they account for about 39 percent of expected EC/INS benefits. Some 65 percent of these benefits are realized in the Gulf of Mexico and the New York region. The expected benefit for this combination of vessels and regions for EC systems at the 50/25/25 effectiveness level is $530 million. Estimating the cost of producing and maintaining the digital chart data for the critical regions at $50 million, the total cost of this alternative is expected to be about $100 million (scenario 3, Table 5).

If more sophisticated INS equipment can achieve more optimistic effectiveness levels, its use on tank vessels and large tank barges in critical regions can be justified even at higher equipment cost (perhaps $100,000 per vessel). This scenario (scenario 4, Table 5) is analogous to scenario 2, but produces benefits in excess of $1 billion at a cost of $150 million.

Table 5

Benefits and costs of policy options representing selected combinations of technologies. All figures in 1995 dollars, covering the future study period 1996-2010, at 10% real discount rate.

policy scenario (i)	benefit ($B_i = L_0 - L_i$)	cost (C_i)	net benefit ($B_i - C_i$)	benefit/cost (B_i/C_i)
1: ECs @ 50/25/25, all regions & vessels	$2.09 b	$750 m	+$1.34 b	2.8
2: ECs @ 25/10/10, all regions & vessels	$920 m	$750 m	+$170 m	1.2
3: ECs @ 50/25/25, crit. regs., tank ves. only	$530 m	$100 m	+$430 m	5.3
4: INS @ 75/50/60, crit. regs., tank ves. only	$1.02 b	$150 m	+$870 m	6.8
5: VTS in all PNS ports	$840 m	$340 m	+$500 m	2.5
6: VTS in positive net benefit PNS ports	$770 m	$190 m	+$580 m	4.1
7: double hulls for tank vessels, as in OPA	$1.4 b	$6.1 b	-$4.7 b	0.2
8: INS and VTS: comb. of (4) and (6).	$1.60 b	$340 m	+$1.26 b	4.7
9: INS, VTS, and double hulls: (8) and (7)	$2.7 b	$6.4 b	-$3.7 b	0.4

Since VTS and double hulls already are required or implemented, to some extent, in U.S. waters, it makes sense to consider these technologies in combination.

If EC/INS and VTS are implemented together, some projected EC addressable accidents will not occur because they will be prevented by VTS, and vice-versa. This overlap must be accounted for by reducing the combined benefit estimate accordingly. For example, in scenario 8 of Table 5, we assume that INS is installed on tank vessels (as in scenario 4) and that VTS is installed in the positive net benefit PNS ports (scenario 6). Since the overlap in this case is limited to tank vessels, we assume for scenario 8 that one quarter of the VTS benefit is "duplicated" by INS.

Similar considerations hold for the combined effect of double hulls with VTS or with EC/INS. The tanker fleet serving U.S. waters is being converted to double hulls, driven by liability concerns and by requirements of the Oil Pollution Act of 1990 (OPA 90, P.L. 101-380) and MARPOL Annex 1.

Assuming that 40-70% outflow reduction is realized from this conversion to double hulls, we can expect a reduced level of losses associated with tanker casualties in U.S. waters in the future. A rough calculation suggests that the advent of double hulls might reduce the present value of benefits realized from either VTS or electronic charts between 1996 and 2010 in the absence of double hulls by 10 to 20 percent (scenario 9, Table 5). Beyond 2010, when virtually all tank vessels are expected to have double hulls, the reduction may be twice as great.

The analyses summarized in Table 5 suggest that, when applied to large tank vessels, EC/INS can claim benefit-cost ratios of the same magnitude as, and quite likely greater than, VTS. Both EC/INS and VTS appear clearly superior on this criterion to double hulls. The benefit-cost ratio of integrated navigation systems for tank vessels in critical regions (scenario 3, Table 5) is close to the highest mark achieved by any PNS VTS study zone (New Orleans, B/C of 7.9). At the low end of effectiveness, it appears that EC systems must prevent at least 25 percent of addressable groundings and 10 percent of addressable collisions and rammings to be justified on safety grounds alone for all commercial vessels.

Double hulls have been adopted as requirements by U.S. law (OPA 90, P.L. 101-380) and by international convention (MARPOL Annex 1). The U.S. Coast Guard has installed a new VTS facility in Prince William Sound, and plans to install or improve VTS in perhaps a dozen other U.S. ports over the next 15 years, though some uncertainty remains regarding the implementation of these plans. The fact that these alternatives are being pursued as a matter of U.S. policy, and the benefit-cost advantage enjoyed by electronic charts, suggest that electronic charts deserve greater attention and higher priority than they have received to date.

6. CONCLUSIONS

Electronic charts and integrated navigation systems at an intermediate level of effectiveness (preventing about one third of potentially addressable accidents) could help avoid an estimated 3000 accidents involving commercial vessels in U.S. waters between 1996 and 2010, assuming no significant changes in underlying casualty rates. The expected overall cost of these accidents is estimated to be about $2.1 billion (1995 dollars).

Using a benefit-cost criterion, electronic charts compare favorably to double hulls and VTS as a technological alternative in the effort to reduce the cost of accidents in maritime transportation. A properly targeted application of integrated navigation systems to large tank vessels and tug/barges operating in the Gulf Coast and New York regions could realize a theoretical benefit/cost ratio of almost 7:1 from safety benefit alone, in the absence of new VTS installations and double hulls. Even in combination with improved VTS and double hulls, electronic charts and integrated navigation systems are expected to have significant positive net benefits, since they provide improved safety over a wider geographic area than VTS coverage. Modern navigation technologies are likely to produce efficiency benefits in addition to the safety benefits we have examined in this paper. The fact that double hulls and VTS are being pursued as a matter of U.S. policy, and the benefit-cost advantage enjoyed by EC/INS, suggest that electronic charts deserve greater attention and higher priority than they have received to date.

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