Fuel Efficiency of Ships and Aircraft

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Abstract:

This paper examines past trends in the fuel efficiency of ships and aircraft, and looks at current technical developments which could yield further improvements. The period to 2005 receives attention because of the Toronto Target to reduce greenhouse gas emissions by 20% from 1988 levels by this date.

The paper presents preliminary results from simple spreadsheet models used to estimate the future fuel efficiency of the Australian fleets of ships and aircraft in both domestic and international use. The models take account of the current composition and probable replacement patterns of the Australian fleets; and the likely improvements in fuel efficiency from technical developments.

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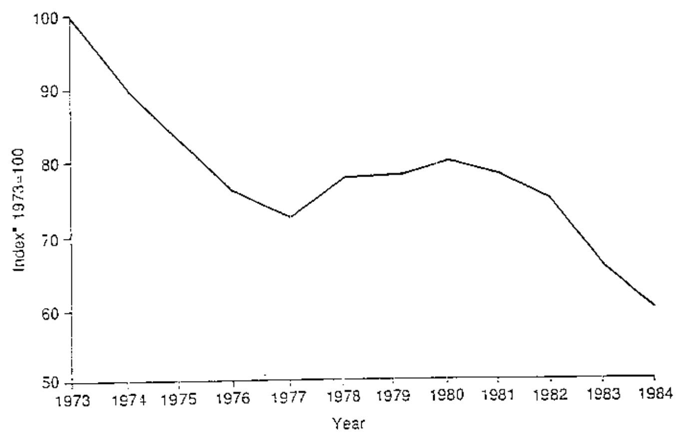
Introduction

This paper was prepared in connection with the Bureau's project on greenhouse gas emissions from Australian transport. The initial impetus for the paper was a request from the Australian Bureau of Agricultural and Resource Economics (ABARE) for information regarding trends in fuel consumption rates for ships and aircraft to assist it in formulating its projections of Australian energy usage.

Fuel efficiency of ships

Over the past 20 years there has been a considerable improvement in the fuel efficiency of shipping. Figure 1 shows a graph of an index of the energy intensity of world shipping from 1973 to 1984 (IEA 1987) which shows a high rate of improvement in the mid-1970s and in the later part of the period covered.

Figure 1 Index of energy intensity in world shipping



a Index based on world bunker oil demand divided by laden ton-miles

Source International Energy Agency (1987)

Table 1 shows data for the average fuel efficiency of those vessels of the Australian flag fleet wholly or partly engaged in the coastal trade, presented by the Australian National Maritime Association (ANMA) to the IAC inquiry into coastal shipping (IAC 1988). ANMA attributed these improvements in fuel economy to increasing ship size, to lower design speeds, more energy efficient engine technologies,

TABLE 1 CHANGES IN FLEET FUEL EFFICIENCY 1975 TO 1987 (TONNES/DAY/000DWT)

	1975	1980	1985	1987
GENERAL CARGO	3.68	4 13	3 22	2 97
DRY BULK	1 04	0 92	0.74	0 52
TANKERS	1.23	1.14	0.86	0.75

Source IAC (1988) - ANMA submission no 38 pp18-22.

improved hull designs and surface finishes (eg self-polishing antifouling paints). A Department of Transport and Communications (DOTC) source considered that the big improvements in fleet fuel efficiency have been made, as the ships built when fuel was not so big a cost factor have largely been replaced. Table 2 shows some examples of the gains in the fuel efficiency of particular sizes of ships, both coastal and overseas trading vessels.

TABLE 2 COMPARISON OF FUEL CONSUMPTION OF EXAMPLES OF REPLACEMENT SHIPS IN THE AUSTRALIAN FLAG FLEET

	TYPE	SIZE	SPEED (knots)	FUEL CONSUMPTION PER DAY
1981 replaced by	BULK	141 000DWT	14	60 TONNES FUEL OIL + 1 5 TONNES DIESEL
1985	BULK	148 000DWT	14	45 TONNES FUEL OIL + NIL DIESEL
1968 replaced by	TANKER	19 000DWT	14	36 TONNES FUEL OIL
1989	TANKER	32 000DWT	13	19 TONNES FUEL OIL
1974 replaced by	BULK	27 000DWT	15	36 TONNES FUEL OIL + 2 TONNES DIESEL
1984	BULK	37 000DWT	15	25 TONNES FUEL OIL + NIL DIESEL

Source Department of Transport and Communications.

The move from steam turbines and gas turbines to diesels after 1974 gave a large fuel efficiency increase (see table 3), which is unlikely to be repeated. With the high level of thermodynamic efficiency now reached by many engine designs, the pace of development could be said to have slowed down (*The Motor Ship* 1989a).
Earlier 'a huge amount of engine research and development possibilities' had been referred to, although presumably with diminishing returns in terms of gains in efficiency (*The Motor Ship* 1988b). For larger engines, no great improvements in overall engine efficiencies were foreseen, but increases in propulsion system

TABLE 3 EXAMPLES OF INCREASES IN MARINE ENGINE EFFICIENCY

	(grams of fuel / horsepower / hour)	
gas turbine	1950s	230-350
4 stroke medium speed diesel	1967	153-162
	1988	126-129
2 stroke low speed diesel	1963	155
	1968	155
	1976	144
	1979	133
	1982	116

Note In 1980 there was a 20% thermal efficiency gap between diesel and steam turbines which Harrold considers would be larger today and unlikely to be closed

Source Harrold (1989)

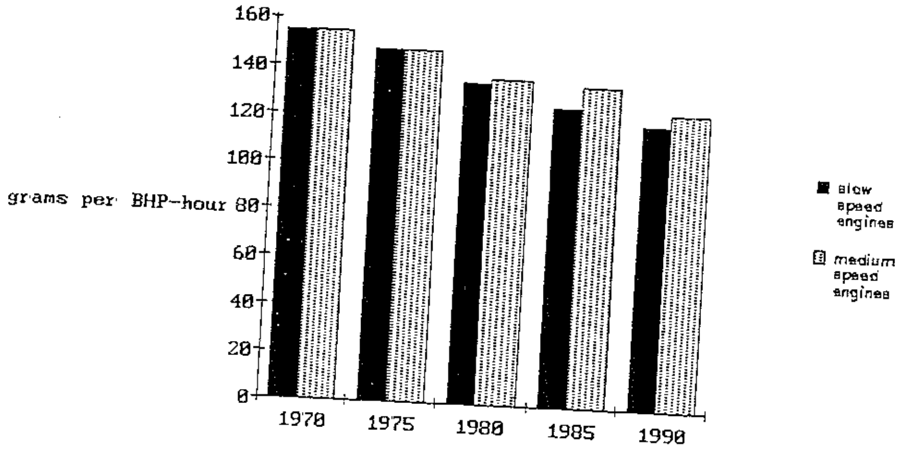
efficiency were considered still possible For smaller ships, the latest medium speed diesels have created an active re-engining market. For one major manufacturer, the percentage of its output going to re-enginings has risen from about 10% in 1970 to about 40% in 1987-89. (*The Motor Ship* 1989b).

Figure 2 shows the past rate of improvement in the fuel efficiency of marine diesel engines (Verhelst 1990). Increased efficiency is claimed for new larger bore, slower running diesel engines. The low speed diesel had 73% of the overall market on a bhp-installed basis in 1989, and it is considered that the diesel will remain the dominant prime mover for merchant ships in the foreseeable future (*Seatrade Business Review* 1989a). New engine layouts, such as 'father and son' combinations (The Motor Ship 1988a, 44) offer the possibility of considerable efficiency gains in vessels which have several common operating speeds, such as cruise ships.

Industry publications are reporting efficiency gains from new hull appendages aimed at wake vortex smoothing, from new propeller arrangements, and from wider use of less-refined fuels, as well as continuing gains from new engine technology (including ceramic coatings, and better, more automated engine monitoring and management systems). For example, recent advances in engine design, hull forms and propeller layout are claimed to deliver gains of 20% for Very Large Crude Carrier (VLCC) tankers over tankers delivered 2 years previously, and some 50% less overall fuel consumption than earlier generations of VLCCs (*Seatrade Business Review* 1989b).

Regarding hull appendages, the Schneekluth wake equalising duct, fitted or retro-fitted to the stern of a vessel just forward of the propeller, is said to give fuel savings which pay back the capital cost of installation in as little as one year (*Seatrade Business Review* 1990). However Patience (1990, 110) notes that while it is "generally accepted that this type of device can improve an inferior hull", it is "unlikely to prove very effective for a properly designed hull and aft end combination".

Figure 2 Improvement in the rate of fuel consumption of marine diesel engines



Source Verhelst (1990)

For propellers, even features as simple as ribs on the blades of a conventional propeller have been claimed to offer propulsive efficiency gains of 20 to 30%, by converting to useful work the energy usually lost as turbulence (*Seatrade Business Review* 1989b) Contra-rotating propeller systems are claimed to yield energy savings of up to 16% (Seatrade Business Review 1990, 101), and wider application was then awaiting higher bunker prices to provide more attractive payback times. The Grim vane wheel (a free-running propeller aft of the main propeller) is claimed to offer propulsive efficiency gains of up to 7% for VLCCs (*Seatrade Business Review* 1989b)

Emulsified fuels, wherein water is mixed with fuel oil at concentrations of 16 per cent or so, have been claimed to give savings of 4% in fuel consumption through the catalytic effect of the water vapour released in the cylinder, which helps to atomise the fuel and intensify the fuel/air mixing process. Reductions in exhaust emissions of oxides of nitrogen and carbon monoxide are claimed, together with reduced carbon deposits and exhaust gas temperatures, which reduce maintenance. Ten bulk carriers of a USSR shipping line had been fitted with this system by 1989 (*The Motor Ship* 1989c).

Computerised engine monitoring and diagnostic systems are being developed by engine manufacturers, which continuously monitor the combustion process to ensure that engine settings are always maintained at their optimum levels.

These systems could have an important contribution to make to efficient operation (*The Motor Ship* 1989d). A related area is precision voyage control systems or adaptive autopilots, such as the ETA-pilot, which uses an on-board microcomputer to monitor and control voyage parameters such as speed (either a set speed or a speed calculated to maintain schedule), the optimal combination of revolutions and propeller pitch, and rate of fuel consumption, for various conditions of draught and trim (Fahlgren 1987).

However, while there have been recent trends towards greater fuel efficiency in conventional shipping, some recent and projected developments could act in the opposite direction. One example is the wave-piercing catamaran, such as the Sea Cat Tasmania, a high speed passenger / car ferry. Another is the SWATH (small waterplane-area twin-hull) 50 knot cargo catamaran projected for the year 2000 by Japanese shipbuilders. Especially in times of high interest rates shippers with high value cargoes may be willing to pay for fast transit times from such speeds. Ship operators facing high capital costs may find it economic to run conventional shipping at higher speeds when shipping markets are short.

Potential fleet fuel efficiency gains to 2005

There appear to be potential steady incremental fuel efficiency gains to be realised over the next 15 years, from replacement of existing vessels and from ongoing technical progress in engine, hull and propeller design.

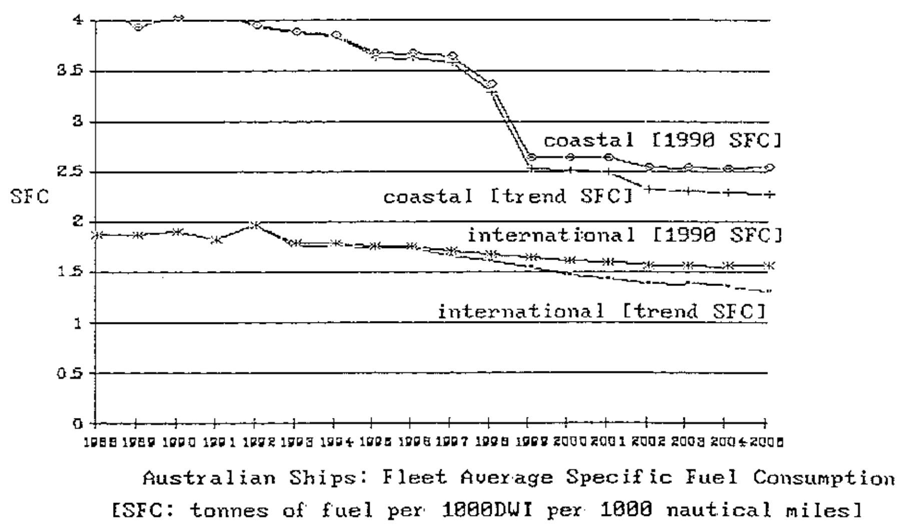
Recent Australian ship replacements with more fuel efficient (and smaller crewed) vessels have been a result of the Ships Capital Grants scheme (1987) and the Maritime Industry Development Committee (MIDC) scheme. Up to 1992, the original cut-off for the Ships Capital Grants scheme, 27 vessels have been ordered, of which 23 are already in service. Some new vessels (such as LNG carriers) are for new trades rather than replacements for existing vessels. The scheme has been extended to 1997, and a few more ships have already been ordered. A DoTC source expected that by 1997 just about all other ships built before 1982 in the major trading fleet (which excludes small vessels such as landing barges, and which now totals 74) will have been replaced or have had replacements ordered.

So about 60 to 70 per cent of the existing Australian flag major trading fleet will probably be replaced by 2005, with vessels which could be some 15 to 25 per cent more fuel efficient if replaced today. As well, by the time many of these vessels do come to be replaced, efficiency gains of another 10 to 15 per cent could well be available. On this basis, the average efficiency of the Australian flag fleet could well rise by some 20 to 25 per cent on a fuel consumption per thousand deadweight tonnes (1000DWT) per hour basis by 2005.

A spreadsheet model is being developed which lists each ship (over 2000 DWT) of the Australian coastal and international fleets and its fuel consumption per day. It was assumed, unless more definite information was available, that ships would be replaced at age 15 years (or 1992 if this age was reached earlier). The fuel consumption of each replacement vessel was estimated from regression equations for particular types of vessels. A fleet average fuel consumption, weighted by deadweight tonnage, was calculated for each year up to 2005.

Figure 3 shows preliminary results from this model for Australia's coastal and international ships. The sharp drop in average specific fuel consumption for the coastal fleet between 1997 and 1999 is due to the assumed replacement at that time of four coal burning ships (each using some 200 tonnes of coal per day) with diesel engined vessels each using 30 to 40 tonnes of fuel oil per day. The model indicates trend coastal fleet average fuel consumption falling from 4.15 tonnes of fuel per 1000DWT per 1000 nautical miles in 1988 to 2.27 in 2005, a drop of some 45 per cent. For the Australian flag international fleet, the trend decrease was from 1.87 tonnes of fuel per 1000DWT per 1000 nautical miles in 1988 to 1.31 in 2005, a drop of about 30 per cent. [The model indicates that the fleet averages currently are about 4.09 (coastal) and 1.82 (international), and also that if future replacement ships had 1990 levels of fuel economy, then average improvements of about 39 per cent (coastal) and 17 per cent (international) from 1988 levels would result by 2005.] The model could take account of fuel efficiency gains flow from replacing existing vessels with larger vessels, especially if the modal task were to grow in size, by entering a larger deadweight tonnage into the regression equations. However, it has currently been assumed that vessels are replaced by vessels of the same size.

Figure 3 Trends in the fuel efficiency of Australian ships

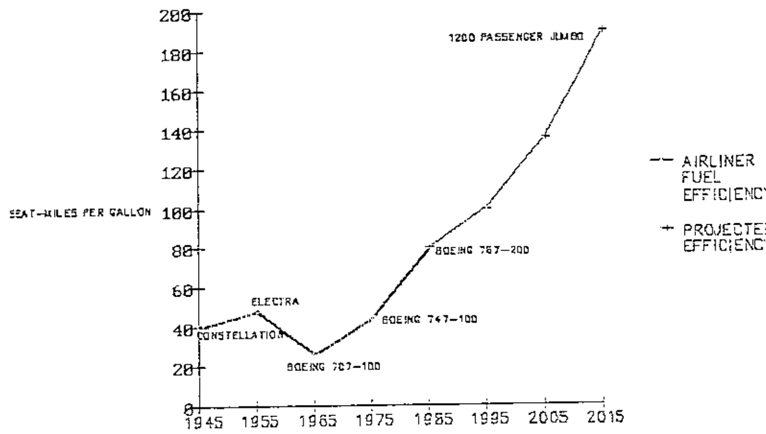


Source preliminary BTCE estimates

Fuel efficiency of aircraft

Figure 4 shows the trend in fuel efficiency (in seat-miles per US gallon) for some examples of airliners from the 1940s up to the Boeing 767-200, with a projection to 2010 showing a continuing rising trend (Sweetman 1984).

Figure 4 Trend in aircraft fuel efficiency

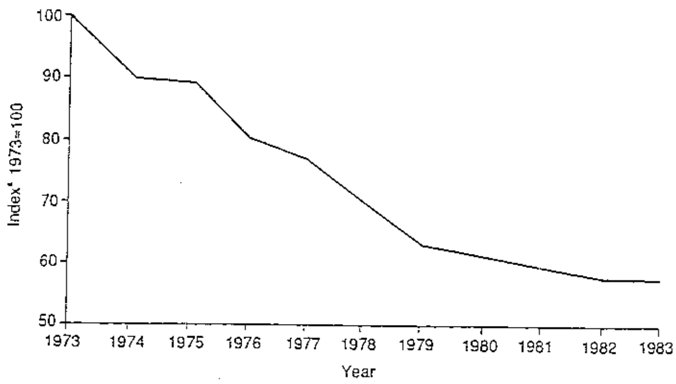


Source Sweetman (1984)

Figure 5 shows a graph of the energy intensity of aviation in OECD countries from 1973 to 1983 (IEA 1987) The overall index of intensity for the aircraft fleets appears to display a slowing of the rate of improvement in the later part of the period covered.

Future fuel economy gains should be available from increasing aircraft size, improved aerodynamics, reduced weight from advanced materials, from progress in engine design and, possibly, from the use of alternative fuels. However, Sweetman (1984) noted that, because of the lifespan of modern airliners, especially wide-bodied planes, many of the aeroplanes which will be operating in 2000 are already in service. Every wide-bodied plane built to date would still be structurally capable of flying in 2000, many with still 10 years of useful life. As well, many of the newer wide-bodied models, such as 767s and A310s should still be in production, as it takes at least 10 years' production to show a profit.

Figure 5 Energy intensity in world aviation



a Index based on consumption of aviation fuel in OECD countries divided by world total of ton-kilometres flown

Source International Energy Agency (1987)

Sweetman (1984) considered the present airliner configuration to be efficient, and noted that very little detailed study of radical configurations was being undertaken, except in the area of powerplants. A recent industry publication noted that only one all-new design was in prospect - the Boeing 777. In 1990 no radical designs, configurations or technology were foreseen, even among possible, rather than probable, developments (*Avmark Aviation Economist* February/March 1990).

Professor David Hensher, in a consultancy report for the BICE (Hensher 1991), reviewed the likely technical advances and the improvement in seat-miles per gallon which might be expected. [New commercial aircraft are expected to offer 65 to 80 seat-miles per US gallon in the early 1990s, compared to 50 to 79 seat-miles per US gallon in 1989] (Hensher 1991). However Hensher notes that many of the new developments are unlikely to be on stream until after 2000, and that the movement to larger, technically more efficient aircraft types will become the most important means of improving fuel efficiency.

Boeing's Commercial Airplane Group President foresaw a still-larger derivative of Boeing's wide-bodied jets by about the end of the century, and that much of the traffic now carried by 140-150 passenger aircraft would then be moved by bigger aircraft (O'Lone 1990). Large "infrastructure friendly" aircraft with up to 1000 seats (long haul) were foreshadowed in *Avmark Aviation Economist* (February/March 1990).

Schmitt (1990), predicting gradual evolutionary progress in design over the next decades, foresaw a potential for overall aerodynamic drag reduction of over 20 per cent. Riblets, microscopically grooved plastic film applied to the fuselage, tail and engine casings of new or existing aircraft was a subject of current research.

Green *et al* (1987) state that one current development aim is to eliminate drag-inducing items such as wing fences, vortillons and vortex generators. Schmitt (1990) also noted the role to be played by weight reduction, using composite materials such as Arall (fibre-coated alloy) or Kevlar, and lighter alloys such as aluminium-lithium.

Major changes in engine design would be needed to repeat the efficiency gains made with the initial introduction of the high bypass ratio turbofan engine. One such, at least for small and medium airliners, could be the prop-fan engine, using 8 or 10 thin, sweptback blades of smaller diameter than a conventional fan. This type of ultra high bypass ratio (UHBR) engine could be either an unducted fan (UDF), with bypass ratio of about 35:1 or, for noise reasons in larger engines, a shrouded fan with bypass ratios of 15:1 to 25:1 (Green *et al* 1987). [The bypass ratio of an engine is the ratio of the total mass of air accelerated by the engine to the mass of air passing through the combustion section of the engine. The ratio varies from zero for a turbojet (as fitted to Concorde), through 5:1 or 6:1 for recent turbofans, 70:1 to 100:1 for turboprops, to a high as 200:1 for propeller aircraft.]

UDF engines could offer 25 to 28 per cent fuel savings, while shrouded prop-fans could offer 19-21 per cent lower fuel consumption than conventional fan engines (*Aviation Week & Space Technology*, April 13, 1987). Lynn (1987) stated that the 100-150 passenger class would be the first main use. Problems of gearbox design still had to be overcome for large units. The UDF had by 1989, in an MD-80 demonstrator, fulfilled its technical promise (Donoghue 1989). However, Donoghue (1989) reported that a major engine producer had decided that the market would not require this type of engine until 1997, and had put back plans to introduce its UDF engine. Woolsey (1990) referred to the UDF engine as 'dormant' in *Air Transport World*'s November 1990 Large Engine Update.

Although US airline manufacturers have apparently decided not to adopt UHBR engines (*Avmark Aviation Economist* September 1990), General Electric is predicting that its GE90 family of large higher by-pass engines will have a 9 per cent improvement in specific fuel consumption over its predecessor.

Refined versions of existing big-fan engines, with high-efficiency compressors, wide-chord fan blades and fully electronic controls, still offer useful improvements in fuel consumption, and will be standard on most engines by the 1990s. Ford (1989) notes that the Rolls Royce RB211-534E4 wide chord fan engine gives specific fuel consumption (SFC) improvements of 4 per cent at maximum cruise speed and 4.75 per cent at maximum climb, compared to its predecessor narrow chord fan engine. [Ford noted fuel efficiency improvements cumulating to an improvement of 16.6 per cent for the Rolls Royce RB211-524 engine from its introduction in 1977 up to the latest version expected to be certified in 1992.] The newer engines also allow the relationship between the core and the by-pass systems to be varied according to the thrust required, slowing the fan at high thrusts, and increasing efficiency.

Ford considered that future engine development would probably involve ultra-high by-pass ratio (UHBR) engines, required for still larger subsonic passenger aircraft. An example could be the contra-fan engine developed by Rolls Royce, which could offer SFC some 15 per cent better than the RB211-524G engine already in service.

In the longer term, liquid hydrogen may become an alternative to jet fuel. Price (1991) states that there appear to be no insurmountable technical problems, although tank size, safety and price are issues. Price notes engine manufacturers' estimates of a 5 to 10 per cent gain in specific fuel consumption. As well, there would be no carbon dioxide or carbon monoxide emissions, although water vapour and oxides of nitrogen produced would create some greenhouse effect.

While there has been a trend towards greater fuel efficiency in conventional subsonic passenger aircraft in recent years, some future developments could act in the opposite direction. For example, any second generation supersonic passenger aircraft, while likely to be more fuel efficient than Concorde (which is about 5 times less fuel efficient than a jumbo jet), would still require a trade-off of fuel efficiency for the increased speed for traffic won from subsonic jumbo jets. [Second generation supersonic business-class passenger aircraft could feature tandem-fan or dual-cycle engines, which would have a high by-pass turbofan for sub-sonic flight and a high-thrust fan for supersonic use (Ford 1989)] Ultra large cargo aircraft (possibly including flying boats), which probably would be more fuel efficient than existing cargo aircraft, could increase overall freight-related consumption of fuel if they were able to win cargoes from conventional shipping.

Potential fleet fuel efficiency gains to 2005

In October 1989, an international agreement was reached at ICAO to phase out all Chapter 2 (jet) aircraft by 2002, in favour of the quieter Chapter 3 aircraft (the Chapters refer to chapters in Volume 1 of the annexe to the ICAO agreement). Chapter 3 aircraft (those certified since October 1977) feature high by-pass, higher fuel efficiency engines, which besides being quieter, are typically 30 to 40 per cent more fuel efficient than their Chapter 2 equivalents, which generally have low by-pass engines

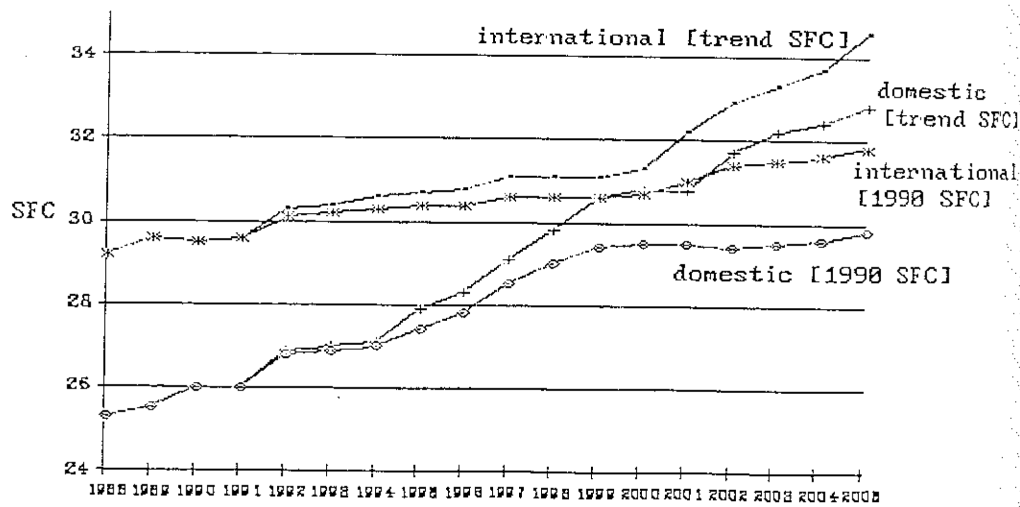
However, this margin could not be applied overall to the 36 per cent of the fleet which (as at 31 December 1990) was Chapter 2, as some of the aircraft are only marginally in the Chapter 2 category. This level of saving might only apply to some 20 to 25 per cent of the current fleet. The Australian Chapter 2 aircraft involved were mainly 727s, F28s, a 707 and a couple of DC9s, together with some of the early 747s, which have high by-pass engines with good efficiency. For wide-bodied aircraft and any aircraft with high bypass engines,the cut-off date is 2002. For other narrow bodied aircraft, the ICAO cut-off is 25 years of age. The Government has decided on a phase out period commencing 1 April 1995, with the proviso that all subsonic jets added to the register after 1 January 1991 must meet Chapter 3 noise standards to be allowed to operate

Gains in the average fuel efficiency of the Australian air fleet over the next 15 years will flow from the replacement of existing Chapter 2 aircraft with

Chapter 3 aircraft and from ongoing technical progress in the design of existing high-bypass engine types fitted to replacement aircraft in the period to 2005. As well, gains may be made from re-engining existing Chapter 3 aircraft with later engines. However, new technology may be required if the past trend is to be maintained. Ultra-high bypass engines, which may or may not become available later in the 1990s, could offer fuel efficiency gains over 1980s generation engines estimated at between 10 to 30 per cent (Hensher 1991).

A spreadsheet model, similar to that for the Australian fleets of ships, is currently being developed to estimate changes in fleet average fuel efficiency from 1988 as the base year. Figure 6 shows preliminary results from this model for Australia's domestic and international aircraft. The model indicates trend domestic fleet average fuel consumption rising from 25.3 seat-kilometres per litre in 1988 to 32.8 in 2005, a rise of some 30 per cent. For the Australian international fleet, the trend increase was from 29.2 seat-kilometres per litre to 34.6 in 2005, a rise of about 16 per cent. The fleet averages currently are about 26.0 (domestic) and 29.6 (international). The model indicates that if future replacement aircraft had 1990 levels of fuel economy, then average improvements of about 16 per cent (domestic) and 9 per cent (international) from 1988 levels would result by 2005.

Figure 6 Trends in the fuel efficiency of Australian aircraft



Australian Aircraft: Fleet Average Specific Fuel Consumption [SFC: weighted average seat-kilometers per litre]

Source Preliminary BTCE estimates

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