

The two prime movers of globalization: history and impact of diesel engines and gas turbines

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Abstract

Modern economic globalization would be impossible without our ability to move billions of tonnes of raw materials and finished goods among the continents and to fly at speeds approaching the speed of sound. These realities were made possible by the interaction of economic and technical factors. Much has been written about their organizational and political underpinnings (ranging from the role of multinational corporations to the history of free trade agreements), but much less on the history of the two prime movers that made these realities possible. Neither steam engines, nor gasoline-fuelled engines could have accomplished comparable feats. Diesel engines made ocean shipping the cheapest mode of long-distance transport and without gas turbines there would be no fast, inexpensive, mass-scale intercontinental travel. This paper examines the history, advances, benefits and costs of the two prime movers.

Introduction

The process of globalization has been examined from many perspectives and with results that have ranged from questionable comparisons to revealing observations. The search for historical precedents has led to such highly arguable claims as Genghis Khan being a thoroughly modern man committed to global commerce.¹ Examination of links between economic globalization and global environmental impacts, a vast realm of cause-and-effect and feedback processes, has become excessively concerned with the emissions of greenhouse gases and the consequences of global warming.² And a simplistic misreading of complex historical, social and economic realities has led to exaggerated claims of a flat world.³

What has been missing, rather conspicuously, is a focus on techniques that have made this unprecedented globalization possible. How did we get to the point of moving billions

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- 1 Jack Weatherford, *Genghis Khan and the making of the modern world*, New York, Three River Press, 2004, p. 267.
 - 2 Richard Alley *et al.*, *Climate change 2007: the physical science basis*, Geneva: Intergovernmental Panel on Climate Change, 2007.
 - 3 Thomas L. Friedman, *The world is flat: a brief history of the twenty-first century*, New York: Farrar, Straus and Giroux, 2005.

of tonnes of fuels, ores, other raw materials and foodstuffs, as well as astonishing varieties of goods (ranging in millions of specifications and in mass terms in hundreds of millions of tonnes), among the continents? How did it come about that we can fly from virtually any place that has a standard-length runway and scheduled commercial service to any other similarly equipped place anywhere on the planet often within just 16, mostly within 24 hours and very rarely in more than 32 hours? And how have these realities changed the course of modern history?

The fundamental way of answering these questions requires looking at the prime movers that energize the fleets of ships and aeroplanes that accomplish these remarkable feats, by contrasting their performance with the capabilities of their less effective predecessors, and then noting the principal consequences of these developments. This sequence is just a segment of studying history's grand sweep as a continuous transition to new prime movers, their invention, introduction, perfection and diffusion and their eventual displacement by more efficient, more reliable and more affordable alternatives.⁴ The greatest reward of this approach is that it informs us about all the critical determinants of the physical process of globalization, as the prime movers clearly delimit the cost, volume, speed and reliability of transfers and trips whose aggregate forms the web of economic and human interaction and integration on a global scale.

The two prime movers that have made the extent and the intensity of today's global economy possible are high-compression non-sparking internal combustion engines invented by Rudolf Diesel (1858–1913) during the 1890s, and gas turbines whose first successful prototypes were designed by Frank Whittle (1907–96) and Hans-Joachim Pabst von Ohain (1911–98) during the 1930s. Understanding the history of these machines and the reasons for their success offers more than just a better appreciation of the forces behind globalization. A lengthy process of the development, commercialization and diffusion of diesel engines provides perfect examples of gradual technical advances that have been receiving very little public attention and that may not be ranked among pivotal modern inventions even by informed professionals – but whose eventual contributions have resulted in epochal shifts in global affairs. Massive two-stroke diesel engines that power supertankers and giant container ships, and ever more powerful, and astonishingly reliable, gas turbines that propel jet aeroplanes are fundamentally more important to the global economy than are any particular corporate modalities or international trade agreements: the latter can be easily changed or abrogated, the former have no equally capable substitutes.

Widespread commercial adoption of the two engines also illustrates the importance of gradual improvements in efficiency, reliability and high-level performance as well as of the accomplishments designed to minimize undesirable environmental impacts of these now ubiquitous prime movers. But before surveying the advances and accomplishments of the two epoch-making techniques I should answer two obvious questions: why are these prime movers qualitatively so different from their predecessors, and why could not the numerous niches they now occupy be filled with comparable efficacy by the first successful internal combustion engine, the four-stroke petrol-fuelled Otto-cycle machine?

4 Vaclav Smil, *Energy in world history*, Boulder, CO: Westview Press, 1994.

Why petrol-fuelled Otto-cycle engines would not do

The history of sparking four-stroke internal combustion engines is remarkable because of a steep learning curve that transformed the pioneering, heavy, horizontal machines into the lightest known, yet increasingly more powerful and more efficient, prime movers suitable for mobile applications. This transformation can be most revealingly traced by their declining mass/power ratios. Comparisons with human and animal labour set the stage for these remarkable achievements. Humans – with a body mass of 60–80 kilograms (kg) and able to sustain power of 60–80 watts (W) – need about 1,000 grams per watt of useful exertion. Draft animals have similarly high mass/power ratios: a well-fed horse weighing 750 kg and developing one horsepower (that is 745 W) will need almost exactly 1,000 g/W. These mass/power ratios are too high to sustain rapid long-distance transport of loads on land or fast movement of heavy cargoes on water.

The earliest steam engines had a mass/power ratio as high as human or animal muscles, but by the second half of the nineteenth century higher engine pressures lowered it to less than 200 g/W. In contrast, the first non-compressing coal gas-fuelled internal combustion engines of the mid-1870s had a mass/power ratio of about 900 g/W, which made them as heavy as animate prime movers and much heavier than a steam engine of the same capacity.⁵ This disadvantage was reversed within a single generation that followed the patenting of the first practical design by Nicolaus Augustus Otto (1832–91) in 1877.

Otto's innovative four-stroke design, also fuelled by coal gas, had a mass/power ratio as low as 100 g/W.⁶ Lighter, yet more powerful, upright and petrol-fuelled versions for mobile applications were introduced during the mid-1880s through the pioneering work of Karl Benz (1844–1929), Gottlieb Daimler (1834–1900) and Wilhelm Maybach (1846–1929).⁷ Improved designs subsequently came at such a rapid rate that in 1901 Maybach's engine powering the Mercedes 35 had a mass/power ratio of just 8 g/W.⁸ Similarly, reciprocating aero engines progressed rapidly from a horizontal machine, designed by Wilbur and Orville Wright in 1903, whose mass/power ratio was still rather high at nearly 9 g/W,⁹ to the American Liberty engine, the standard machine of the US expeditionary force in the First World War that had a mass/power ratio just above 1 g/W.¹⁰

Steady improvements followed after the First World War and the best reciprocating engines available after the Second World War had mass/power ratios lower than 1.5 g/W for automotive applications and well below 1 g/W for air propulsion: the ratio for Wright R-3350 engines (used on the B-29 Superfortress bomber) was as low as 0.66.¹¹ Despite

5 Smil, *Energy*, p. 231.

6 Nicolaus A. Otto, *Improvement in gas-motor engines. Specification forming part of Letters Patent no. 194,047, dated August 14, 1877*. Washington, DC: US Patent Office. As with all US patents, a complete filing is now easily available at Google Patents.

7 Friedrich Sass, *Geschichte des deutschen Verbrennungsmotorenbaues von 1860 bis 1918*, Berlin: Springer, 1962.

8 Jonathan Wood, *Great marques of Germany*, New York: Gallery Books, 1985, p. 89.

9 Bill Gunston, *The development of piston aero engines*, Sparkford, UK: Patrick Stephens, 2001, p. 105.

10 Philip S. Dickey III, *The Liberty engine 1918–1942*, Washington, DC: Smithsonian Institution, 1968.

11 Michael J. H. Taylor, ed., *Jane's encyclopedia of aviation*, New York: Portland House, p. 606–7.

the fact that the mass/power ratio of the Otto-cycle petrol-fuelled engines had improved roughly 100-fold in just 40 years, making them suitable for mobile applications, these spark-ignited engines had several inherent drawbacks that would make them less than perfect prime movers of a globalized economy and that worked against their adoption for high-volume marine shipping, for long-distance trucking and for all longer intranational and intercontinental flights.

To begin with, petrol (US 'gasoline'), their optimum fuel, is always the most expensive product of crude oil distillation. Thermal distillation (separation of oil fractions simply by heating) yields only a relatively small amount of petrol and higher petrol yields can be produced only by expensive catalytic cracking and hydrocracking.¹² In contrast, diesel fuel is blended from less expensive heavier crude oil fractions, and because medium-density and heavy oils dominate the global market their less expensive processing yields more diesel fuel than petrol. Diesel fuel is also nearly 14% heavier than a typical petrol and its energy content is about 12% higher. This means that ships fuelled by diesel fuel could travel, everything else being equal, 12% further than the vessels with equally large stores of petrol. But everything else is not equal: petrol engines are inherently less efficient converters of chemical energy into mechanical energy than are diesel engines.

Efficiencies of petrol engines have increased with higher compression ratios but the peak performance of perfectly tuned and carefully operated modern engines is still no higher than about 30% and rates between 20–25% are much more common.¹³ In contrast, even during its very first certification tests in February 1897, Diesel's engine was more than 25% efficient and subsequent improvements raised the rate to 41% by 1911, approximately twice as high as usual efficiencies of the contemporary petrol-fuelled engines.¹⁴ Best efficiencies of today's largest marine diesels are in excess of 50%,¹⁵ even though they burn a fuel of the lowest quality that is too heavy and too sulfurous to be used on land. The combined advantage of the fuel's higher energy content and the engine's inherently higher efficiency means that diesel engines produce twice as much useful power with an identical volume of fuel than do petrol engines. The higher maintenance requirements and shorter expected service time of petrol engines means that petrol-fuelled ships, trains or trucks would be more than twice as expensive as diesel to operate.

The third major drawback of petrol engines is their spark ignition. The ignition wave propagates downwards but high pressure and high temperature leads to a spontaneous combustion of the fuel that sends a pressure wave in the opposite direction, resulting in a violent engine knock. The only way to avoid this knocking was to hold the compression ratio of early internal combustion engines below 4.3:1, limiting the engine efficiency. A General Motors team, led by Charles F. Kettering, researched the remedial options and by 1921

12 Robert A. Meyers, ed., *Handbook of petroleum refining processes*, New York: McGraw-Hill, 2004.

13 Franz Mandl, F. *Statistical physics*, Chichester: Wiley, 1989, pp. 121–3.

14 Dugald Clerk, 'Oil engine', in *Encyclopaedia Britannica*, 11th edition, vol. 20, Cambridge: Cambridge University Press, 1911, pp. 25–43.

15 Wärtsilä, 'Wärtsilä RT-flex96C and RTA96 (24,000-80,080 kW)', 2007, <http://wartsila.com> (consulted 1 March 2007); MAN Diesel, 'Products', 2007, <http://www.manbw.com/engines> (consulted 1 March 2007).

identified ethanol as an effective anti-knocking ingredient.¹⁶ But during the 1920s large-scale production of ethanol was prohibitively expensive and bromine and iodine alternatives were even more costly.

A GE team led by Thomas Midgley confirmed on 9 December 1921 that tetraethyl lead – $(C_2H_5)_4 Pb$ – was a highly effective anti-knocking agent even when added at concentrations as low as 1/1000 of the fuel's volume.¹⁷ Leaded petrol was marketed in February 1923 and while its use allowed the rise of the compression ratio to the modern range of 8:1–12:1 it carried environmental and health costs. Lead's effect on ecosystems and human health (it poisons the central nervous system and results in deterioration of mental capacities) eventually led to the phase-out of leaded petrol that began in the US in 1975 and was completed by 1990.¹⁸

Diesel engines, with compression-induced spontaneous combustion, do not need any sparking and hence have no knocking. High-performance reciprocating aero engines fuelled by leaded petrol made commercial aviation possible but have the same cost disadvantage when compared to gas turbines.¹⁹ Kerosene is about 11% heavier than petrol and its slightly higher energy content means that a plane could fly about 13% further with the same volume of fuel. The heavier fuel is also cheaper than petrol, it has lower evaporation losses at high altitudes and it is also safer, with a lower risk of fire during ground handling and producing more survivable crash fires. Petrol-fuelled long-distance aviation would not be just more expensive and less safe but also more uncomfortable and tedious.

Vibration produced by up-and-down strokes of pistons is a major source of discomfort and potentially a serious safety matter: it is tolerable as long as the piston pulses are virtually identical but misfiring sparkplugs, leaky valves and worn parts aggravate it, shaking the entire plane and eventually loosening rivets and pivots and also causing dangerous pilot fatigue.²⁰ The ever-present vibration was made worse because of the duration of long-distance flights and by low cruising altitudes. The limited power of reciprocating engines kept the cruising speeds well below 500 km/h. The Douglas DC-3 – the most common and the most durable piston-powered commercial aeroplane ever produced (introduced in 1935) – cruised at just 275 km/h at an altitude of about 6 km, still well within the active layer of the troposphere where aeroplanes encounter frequent turbulence.²¹ And even the four-engine Super Constellation, the fastest and the most powerful post-Second World War airliner, could not manage more than 520 km/h at the same altitude.²²

16 Sigmund A. Lavine, *Kettering: master inventor*, New York: Dodd, Mead, 1960.

17 Thomas Midgley, IV, *From the Periodic Table to production: the life of Thomas Midgley, Jr., the inventor of ethyl gasoline and freon refrigerants*, Corona, CA: Stargazer Publishing, 2001, p. 26.

18 William Kovarik, 'Ethyl-leaded gasoline: how a classic occupational disease became an international public health disaster', *International Journal of Occupational and Environmental Health*, 11, 2005, pp. 384–97.

19 Chevron Products Corporation, *Aviation fuels: technical review*, San Ramon, CA: Chevron Products Corporation, 2000.

20 Robert H. Scanlan and Robert Rosenbaum, *Introduction to the study of aircraft vibration and flutter*, New York: Macmillan, 1951.

21 Taylor, *Jane's*, pp. 338–9.

22 Taylor, *Jane's*, pp. 606–7.

In contrast, the first passenger jet, the British Comet, cruised at about 725 km/h, and today's jetliners cruise at more than 900 km/h at maximum altitudes of up to 12.5 km.²³ Consequently, trans- and intercontinental flights are typically two to nearly four times (when counting the refuelling stops that were necessary on long flights) faster than they were in the piston engine era. And because rapid rotary motion of gas turbines produces much less vibration than the reciprocating motion of piston engines, and because the jets can fly in the highest reaches of the troposphere, well above all but a small fraction of the atmospheric turbulence, jet flights are incomparably smoother.

Global trade in raw materials, foodstuffs and manufactured goods would have certainly grown during the twentieth century even if ships continued to be powered only by steam engines, as would have the intercontinental flights powered by piston engines – but neither endeavour would have reached such capacity, speed and intensity, and done so at such low prices, as has been the case with diesel engines and gas turbines. Their commercialization and worldwide diffusion were governed at least as much by national peculiarities as they were driven by general historical circumstances and by technical and economic imperatives. The eventual outcome – global dominance of these efficient prime movers and their now so indispensable role in sustaining the process of economic globalization and high personal mobility – was a sound theoretical expectation, but the road to technical supremacy and economical indispensability was not (particularly in the case of diesel engines) a matter of inevitable, autonomous advances.

Diesel engines

The genesis of the most efficient internal combustion engine can be traced to an inspiring lecture. As a student Diesel was intrigued when Carl Linde (1842–1934) explained Carnot's theorem and low efficiency of existing engines and pointed out that an engine working under isothermic conditions would convert all heat to work. As Diesel recalled thirty-three years later, 'I wrote in the margin of my college notebook: "Study whether it is not possible to realize in practice the isotherm"?' Then and there I set myself the task! ... Thereafter the wish to realize the ideal Carnot cycle dominated my existence.'²⁴

Diesel only began to work on the project in 1890, after his return to Germany from Paris where he worked for Linde's ice-making company. Much has been written about the fact that by aiming to build an engine that would approach Carnot's ideal thermal cycle (and hence work with the maximum possible efficiency) Diesel set the bar impossibly high, had to settle for a very different design and had to rely on the engineering skills of many collaborators to make even that altered design commercially acceptable. Opinions expressed by contemporary writings have ranged from reaffirming Diesel's inventiveness²⁵ to denigrating his contributions²⁶ but nearly six generations later the magnitude of his achievement is clear.

23 J. Graham Cowell, *D.H. Comet: the world's first jet airliner*, Hounslow: Airline Publications, 1976.

24 Rudolf Diesel, *Die Entstehung des Dieselmotors*, Berlin: Springer, 1913, pp. 1–2.

25 Eugen Diesel, *Diesel: Der Mensch, das Werk, das Schicksal*, Hamburg: Hanseatische Verlagsanstalt, 1944.

26 Johannes Lüders, *Der Dieselmithus: Quellenmässige Geschichte der Entstehung des heutigen Oelmotors*, Berlin: M. Krayn, 1913; Alois Riedler, *Dieselmotoren: Beiträge zur Kenntnis der Hochdruckmotoren*, Wien: Verlag für Fachliteratur, 1914.

Diesel's invention belongs to the category of those admirable nineteenth-century pioneering innovations that were based on theoretical analyses. This was in clear contrast to the first generations of fundamental technical innovations (commonly labelled as the first industrial revolution) that were based overwhelmingly on incremental improvements derived from practical experience and experimentation with existing designs. Watt's steam engine is the best-known example in the latter category. Benoit Fourneyron's pioneering designs of the 1830s for a radial-flow water turbine were obviously based on long experience with shaped horizontal waterwheels.²⁷ And during the first sixty years of the nineteenth century more than a dozen inventors patented and demonstrated inefficient non-compression internal combustion engines.²⁸

In the category of prime movers Diesel's work was thus most akin to Charles Parsons's nearly contemporaneous invention of the steam turbine: it, too, rested on a deep understanding of the laws of thermodynamics and it was built because a theoretical analysis indicated that it could be attempted. Parsons made it clear in his Rede lecture: 'the work was initially commenced because calculation showed that, from the known data, a successful steam turbine ought to be capable of construction'.²⁹ But unlike Parsons, Diesel aimed too high when he tried to construct an engine into which fuel would be introduced at such a rate that the heat of its combustion would balance the heat lost due to the gas expansion and where the temperature inside the cylinder would not rise above the level produced by the compression stroke.

When Diesel found it impossible to construct this nearly isothermal (constant temperature) engine, he opted instead for combustion under constant pressure. This new design still produced an engine of unprecedented efficiency as well as incomparable ruggedness and reliability but its commercialization proceeded much slower than Diesel hoped for, a reality that undoubtedly contributed to his suicide; but decades later, once the engines for specific uses (ships, heavy vehicles, locomotives) were fully developed, they took over their respective niches quite rapidly.³⁰ Diesel's first patent application for a new internal combustion engine was filed in February 1892 and it was granted in December of the same year (Fig. 1).³¹

Heinrich Buz (1833–1918), the director of the Maschinenfabrik Augsburg, and the Krupp corporation supported the subsequent development of a practical four-stroke machine.³² Despite many complications and setbacks a working engine was ready for bench tests by 1897, but far from ready to go into serial production and routine deployment. Its pre-First World War applications remained limited: most notably, it failed to enter the lucrative automotive market, an application for which the inventor naturally had the highest

27 Marcel Crozet-Fourneyron, *Invention de la turbine*, Paris: C. Béranger, 1924.

28 C. Lyle Cummins, *Internal fire*, Warrendale, PA: Society of Automotive Engineers, 1989.

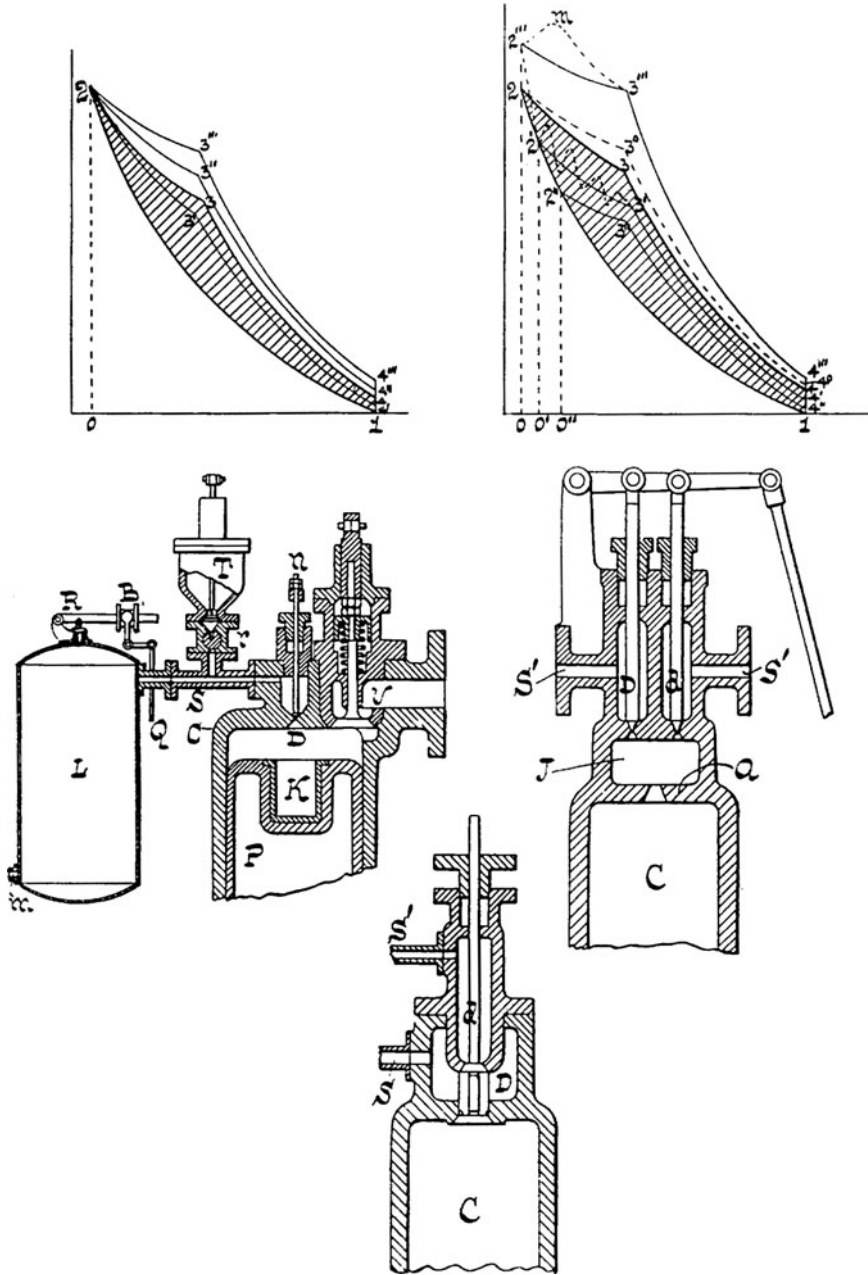
29 Charles A. Parsons, *The steam turbine*, Cambridge: Cambridge University Press, 1911, p. 11.

30 Lynwood Bryant, 'The development of the Diesel engine', *Technology & Culture*, 17, 3, 1976, p. 446.

31 The original German patent (DRP 67,207), 'Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen', was issued on 28 February 1892; the US patent 608,845, filed on 15 July 1895 and issued on 9 August 1898, is now accessible in its entirety at Google Patents.

32 MAN (Maschinenfabrik Augsburg Nürnberg), 'MAN group overview', 2007, <http://www.man.de/index.php?id=714&L=1>

Figure 1. Drawings attached to Diesel's US patent application that was granted in 1898, six years after the German one. The top shows two pressure-volume diagrams of Diesel's engine, and the bottom three images depict details of cylinder heads. The image is available online from the US Patent Office or on Google Patents.



hopes. The engine's relatively high mass/power ratio limited its first applications to stationary uses and to water-borne transport.

The first small diesel engine powered a French canal boat in 1903; this was followed in the same year by a much larger vessel owned by the Nobel brothers and operated on the Volga, and in 1904 by the first (French) submarine. The Danish *Selandia*, the first ocean-going vessel with diesel engines, was launched in November 1911; it had two eight-cylinder four-stroke 932-kW engines and its successful sea trials led to a spate of new orders. It also initiated the development of more powerful, slower two-stroke marine engines by such leading companies as MAN, Sulzer, Krupp and Vickers.³³ Diesel engines only began to make serious commercial inroads during the 1920s and Germany continued to be the centre of their development.

The two important factors – the long tradition of internal combustion engineering and the shortages of petrol in economically deprived post-First World War Germany – drove these developments. Maschinenfabrik Augsburg-Nürnberg (MAN), the successor of Buz's company, made the first direct-injection diesel truck engines in 1924, and it is still one of the world's leading makers of heavy-duty high-pressure engines.³⁴ A key component for these machines came from a company founded by Robert Bosch (1861–1942), another pioneer of automotive engineering. During the early 1920s Bosch engineers were able to overcome the most intractable challenge posed by the accurately timed introduction of fuel into high-pressure engines by producing rapid-rate high-precision injection for diesels, making it possible to develop higher rotation speeds.³⁵

The first diesel locomotives and cars appeared during the 1930s. In 1934 Burlington, Chicago and Quincy's highly streamlined stainless steel *Zephyr* averaged 124 km/h on the more than 1,600-km long run from Denver to Chicago, nearly halving the previous time.³⁶ By the late 1930s the country had ninety streamlined diesel-powered trains, similar trains appeared in a number of European countries but the post-Second World War developments took a different course. Powerful diesel engines eventually displaced all steam locomotives in freight service but the world's fastest passenger trains became energized by electricity.³⁷ The only niche where diesel engines had captured a major share of the market before the Second World War was marine shipping: by 1939 a quarter of the world's merchant fleet was propelled by diesels.

But the conquest was far from decisive: during the Second World War American shipyards built 2,710 Liberty class ships to carry materiel and troops to Europe and Asia, but all of them were powered by oil-fired steam engines.³⁸ The diesel era only truly began after 1945 when the engines were ready to dominate long-distance transport of goods. Two kinds

33 Marine Log, 'Selandia (1912)', 2007, <http://www.marinelog.com/DOCS/cen2.html> (consulted 5 March 2007).

34 MAN (Maschinenfabrik Augsburg Nürnberg), 'MAN group overview', 2007, <http://www.man.de/index.php?id=714&L=1>

35 Friedrich Schildberger, *Bosch und der Dieselmotor*, Stuttgart: R. Wunderlich, 1951.

36 C. Hamilton Ellis, *The lore of the train*, New York: Crescent Books, 1977, pp. 203–4.

37 Vaclav Smil, *Transforming the 20th century: technical innovations and their consequences*, New York: Oxford University Press, 2006, pp. 208–14.

38 John Gorley Bunker, *Liberty ships*, New York: Arno Press, 1972.

of vessels were needed in ever larger volumes: large tankers (wet-bulk carriers) to bring crude oil from the Middle East, Venezuela, Indonesia, and later also from Africa, and dry-bulk carriers to transport loose cargo (grain, ores or coal) that is loaded directly into a ship's hold. The first true tanker, a vessel of just 300 t, was launched in 1884, and half a century later typical ships carried only about 10,000 t.³⁹ In contrast, the post-1945 growth was so rapid that the supertanker designation had shifted from 50,000 deadweight tonne (dwt: carrying capacity plus the weight of ship's fuel) ships before the mid-1950s to 100,000 dwt (the first one launched in 1959) and then to 200,000 dwt vessels (in 1966).

By 2005 the world tanker fleet had about 4,800 ships with an aggregate capacity of 331 million dwt of which roughly 40% were very large crude carriers (VLCC, 240,000–350,000 dwt).⁴⁰ This growth was driven by two key factors: the need to accommodate the steadily increasing volume of intercontinental oil shipments (and later also increasing exports of refined products) and the quest for lower transportation costs. The makers of diesel engines kept up with the demand for more powerful and yet more efficient designs by designing and introducing two-stroke diesels of unprecedented capacity and admirable reliability.⁴¹

The largest diesel engines now have cylinder bores of just over 1 m and their strokes are well in excess of 2 m (for comparison, the analogical measures in my car, a Honda Civic, are 7.5 and 9.0 cm). The quest for reduced transportation costs was also behind the introduction of the first specialized dry-bulk carriers in 1950. By 2005 there were about 6,500 ships of this kind with a total capacity of about 300 million dwt.⁴² Most of them are in either Handysize (up to 10,000 dwt (about a third) or Handymax (up to 35,000 dwt) categories, but 10% of them are large Capesize ships (80,000–200,000 dwt) that account for 30% of all capacity. They are powered by engines rated between 11–17 MW and travel typically at 26 km/h.

But the impressive growth of oil tankers and dry-bulk carriers was surpassed by the recent pace of expansion of container shipping. The container era of global transportation began on 26 April 1956 when Malcolm Purcell McLean (1914–2001), a North Carolina trucker, sent an adapted Second World War-era T-2 tanker, *Ideal X*, from Port Newark, New Jersey, to Houston with 58 large (35 ft) containers (altogether about 1,000 t) set on the ship's strengthened deck.⁴³ In 1960 the first specifically designed cellular ship (with cell guides for vertical stacking of containers) had a capacity of 610 TEU; by the late 1960s the maxima were up to 1,300 TEU, and in 1969 Richard F. Gibney introduced the TEU (Twentyfoot Equivalent Unit) as the common denominator for different sizes of

39 Mike Ratcliffe, *Liquid gold ships: a history of the tanker, 1859–1984*, London: Lloyd's of London Press, 1985.

40 MAN B&W Diesel, *Propulsion trends in tankers*, Copenhagen: MAN B&W Diesel, 2005.

41 MAN B&W Diesel, *Tankers*, pp. 10–11.

42 MAN B&W Diesel, *Propulsion trends in bulk carriers*, Copenhagen: MAN B&W Diesel, 2006.

43 Smil, *Transforming*, p. 222. Three recent books examine in detail the globally transformative impact of this innovation: Frank Broeze, *The globalisation of the oceans: containerisation from the 1950s to the present*, St John's: International Maritime History Association, 2002; Marc Levinson, *The box: how the shipping container made the world smaller and the world economy bigger*, Princeton, NJ: Princeton University Press, 2006; Brian J. Cudahy, *Box boats: how container ships changed the world*, New York: Fordham University Press, 2006.

shipping containers. Lengths of 35 and 24 feet were used by the pioneering shippers (Sea-land and Matson) but the trade became eventually dominated by 20–40 ft long and 8 ft wide steel boxes with reinforced edges and corners; width is the only fixed dimension in order to fit on trucks for intermodal transport.

By the late 1970s came vessels with 3,000 TEU,⁴⁴ in 1996 the *Regina Maersk* was the first ship with 6,000 TEU, a decade later the *Emma Maersk* became the first vessel able to carry 11,000 TEU, and ships of 18,000 TEU may be built in the future.⁴⁵ Capacities of diesel engines rose from about 15 MW needed for 2,000-TEU ships to 81.3 MW (14 cylinders) for the *Emma Maersk*, and 103 MW would be needed for a future 18,000-TEU vessel.⁴⁶ The cellular fleet surpassed 500 vessels in 1977, reached 1,000 ships by 1982 and totalled just over 4,000 vessels in 2007, but because of the faster growth of the largest ships its aggregate capacity expanded from less than 500,000 TEU in 1977 to more than 9.5 million TEU by 2007.⁴⁷ Virtually all non-bulk materials and commodities now move in containers. Cars are the obvious exception: millions of them are shipped annually from Japanese, South Korean, European and US factories to customers around the world by using roll-on-roll-off vessels, but these, too, are powered by large diesel engines.

Gas turbines

The idea of the gas turbine – an internal combustion engine where the introduction of fuel, compression, ignition, combustion and ejection of hot gases do not take place (as in Otto’s or Diesel’s engines) intermittently in sequenced stages but concurrently and continuously in different parts of a machine – was in evidence during the last decade of the nineteenth century. Sanford Moss conceived the engine in 1895, and two designs were patented independently for the first time in 1899 by Franz Stolze and Charles Curtis.⁴⁸ But experimental machines built during the next thirty years either produced no net power or had efficiencies inferior even to those of steam engines. Practical designs emerged only on the eve of the Second World War and their invention provides – together with Alexander Graham Bell’s and Elisha Gray’s patenting of the telephone, and Charles Hall’s and Paul Héroult’s introduction of aluminium smelting – one of the most momentous examples of parallel innovation.⁴⁹ The contest was not as close as Bell’s and Gray’s patent filing on the same afternoon, and the complexity of the machine made it impossible to turn the concept into a working prototype as rapidly as Hall’s and Héroult’s electrode furnaces.

44 MAN B&W Diesel, *Propulsion trends in container vessels*, Copenhagen: MAN B&W Diesel, 2004, p. 1.

45 Maersk Line, ‘*Regina Maersk*’, 2007. <http://about.maersk.com/en/Fleet/Container/ContainerPostPanamax/SeriesK/ReginaMaersk.htm> (consulted 9 March 2007); Maersk Line, ‘*Emma Maersk*’, 2007. http://www.maerskline.com/link/?page=brochure&path=/about_us/facts_and_figures/emma_facts (consulted 9 March 2007).

46 MAN B&W Diesel, *Container vessels*, pp. 7–8.

47 Barry Rogliano Salles, ‘The containership market in 2005’, 2006. <http://www.brs-paris.com/annual/annual-2006/container/container-a/container-a.php> (consulted 9 March 2007)

48 Andrew Nahum, *Frank Whittle: invention of the jet*, Cambridge: Icon Books, 2004, p. 95; Anonymous, ‘First practical gas turbines’, *New Steam Age* 1, 1, pp. 9–10, 20.

49 Smil, *Transforming*, p. 66.

Frank Whittle worked in the tradition of Parsons and Diesel as he approached his design from theoretical thermodynamic and aerodynamic principles whose understanding made it possible, as one of his colleagues put it, to outline the engine's performance 'with the precision of Newton'.⁵⁰ Both Whittle and Hans Joachim Pabst von Ohain began their work as outsiders and their work did not gain an immediate interest from established engineering companies whose expertise was needed to turn the new ideas into reliably working prototypes. But once this happened the advances came rapidly. In Whittle's case only about five years elapsed between the establishment of his Power Jets Ltd in March 1936 (his turbojet patent was filed in January 1930) and the first flight test of the W.1 engine mounted on the Gloster E.28/29 on 15 May 1941.⁵¹ In von Ohain's case the progress was even faster: he patented his turbojet in 1935, the first experimental engine was completed in co-operation with Max Hahn and Ernst Heinkel's engineers in March 1938, and on 27 August 1939 its enhanced version powered the Heinkel-178 piloted by Erich Warsitz during its first flight.⁵²

The two inventors also shared the exclusion from the subsequent development of the engines. Rolls-Royce (RR) was eventually (in 1942) chosen to commercialize the British engine and has remained the world's leading designer of gas turbines ever since. Wright's prototype was shipped to General Electric's (GE) factory in Lynn, Massachusetts, already by 1940, providing the foundation of GE's subsequent excellence in jet engines.⁵³ In Germany the developmental work was transferred to Junkers, where Anselm Franz designed the world's first mass-produced jet engine used in the Messerschmitt Me-262, the world's first operational jet fighter.⁵⁴ Both the Me-262 and the British Gloster Meteor entered the Second World War too late (in July 1944) to make a difference, but the postwar development of military engines, fuelled by the Cold War rivalry, proceeded at a rapid pace.

The three companies whose turbojet prototypes were based on Whittle's W.1 – GE, Pratt & Whitney (P&W) and RR – still dominate the global market for jet engines for civilian aeroplanes. But the first commercial jetliner, the de Havilland Comet 1 used in 1952 and 1953 on routes from London to Johannesburg, Singapore and Tokyo, was powered by four de Havilland Ghost turbojets. The low power and low thrust/weight ratio of Ghost turbojets made the Comet prone to over-rotation and loss of acceleration during

50 Kenneth Fulton, 'Frank Whittle (1907–96)', *Nature* 383, 6595, p. 27; Whittle's US patent (2,404,334, 'Aircraft Propulsion System and Power Unit') is readily accessible at Google Patents; the best website devoted to Whittle's achievements is maintained by the Department of Engineering, University of Cambridge, 'Sir Frank Whittle OM KBE CB FRS', <http://www-g.en.cam.ac.uk/125/achievements/whittle/whitt-r.htm> (consulted 11 March 2007).

51 The precarious existence of Power Jets, Whittle's company, its eventual nationalization and subsequent development of British jet engines are described in detail in Andrew Nahum, *Frank Whittle: invention of the jet*, Cambridge: Icon Books, 2004, pp. 23–51 and 108–32. For different perspectives on these events see Frank Whittle, *Jet*, London: Frederick Muller; John Golley and Frank Whittle, *Whittle, the true story*, Washington, DC: Smithsonian Institution Press, 1987; and Edward W. Constant, II, *The origins of the turbojet revolution*, Baltimore, MD: Johns Hopkins University Press, 1980.

52 Margaret Conner, *Hans von Ohain: elegance in flight*, Washington, DC: AIAA, 2001.

53 Nahum, *Frank Whittle*, pp. 102–3.

54 Cyrus B. Meher-Homji, 'Anselm Franz and the Jumo 004', *Mechanical Engineering* 119, 9, 1997, pp. 88–91. Pioneering contributions of other German engineers – Herbert Wagner and Helmut Schelp – are described in Wolfgang Wagner, *The history of German aviation: the first jet aircraft*, Atglen, PA: Schiffer Publishing, 1998, and in Constant, *Turbojet revolution*, pp. 195–207.

the takeoff.⁵⁵ But the engines were not the Comet's undoing: three catastrophic crashes in 1953 and 1954 were traced to fatigue-caused rupture of the pressurized fuselage that originated around the plane's square window frames.⁵⁶

By the time a completely redesigned Comet 4 entered the service in October 1958 there was a superior jetliner in regular service, Boeing 707 based on B-47 bomber, with four P&W's turbojets (at 84 kN each roughly four times more powerful than a Ghost, with a thrust/weight ratio of 3.5-4.0), the first airliner in Boeing's long succession of commercial jets.⁵⁷ But turbojets based on military designs were not the best choice for large passenger planes and the post-1960 expansion of long-distance traffic has been based on more powerful, yet more efficient, turbofan engines.⁵⁸ Turbofan engines used some of their power to compress more of the incoming air by an additional set of large-diameter fans positioned in front of the compressor.

This air, compressed to only about twice the inlet pressure, entirely bypasses the combustion chamber, an arrangement that reduces fuel consumption, generates higher thrust and (as the high-speed exhaust is surrounded by slower and more voluminous bypass air) produces less noise. Most importantly, turbofans (unlike turbojets) have peak thrust during low speeds, an obvious advantage when getting massive wide-body jets airborne: a fully loaded Boeing 747-400 weighs about 397 t at take-off, and the Airbus 380-800 has a maximum take-off weight of 560 t. In 1955 RR pioneered turbofan engines with its JT3D Conway whose bypass ratio (bypass/core flow) was merely 0.3; a decade later, in 1966, P&W's JT9D engine had a bypass ratio of 4.8.⁵⁹

Four of these engines powered the Boeing 747, the first (in scheduled service since 1970) and still the most successful wide-body jet that revolutionized intercontinental travel.⁶⁰ During the 1980s bypass ratios rose to 6.0, and the most powerful engine that entered service during the 1990s, GE's GE90, had a bypass ratio of 9.0, which means that 90% of all air does not pass through the engine core (Fig. 2).⁶¹ The most advanced version of this engine is almost

55 Laurence K. Loftin, *Quest for performance: the evolution of modern aircraft*, Washington, DC: NASA, p. 410.

56 Nahum, *Frank Whittle*, pp. 145-53; an easily accessible illustrated account is Royal Air Force Museum, 'Comet - the first jet airliner', 2003, <http://www.rafmuseum.org.uk/london/exhibitions/comet/index.cfm> (consulted 13 March 2007).

57 Including 737, the most successful jetliner in history, the pioneering wide-body jumbo 747 and the soon-to-be-launched 787, the most efficient passenger aeroplane ever. Boeing's corporate website with details on its commercial aeroplanes is at <http://www.boeing.com/commercial/index.html>

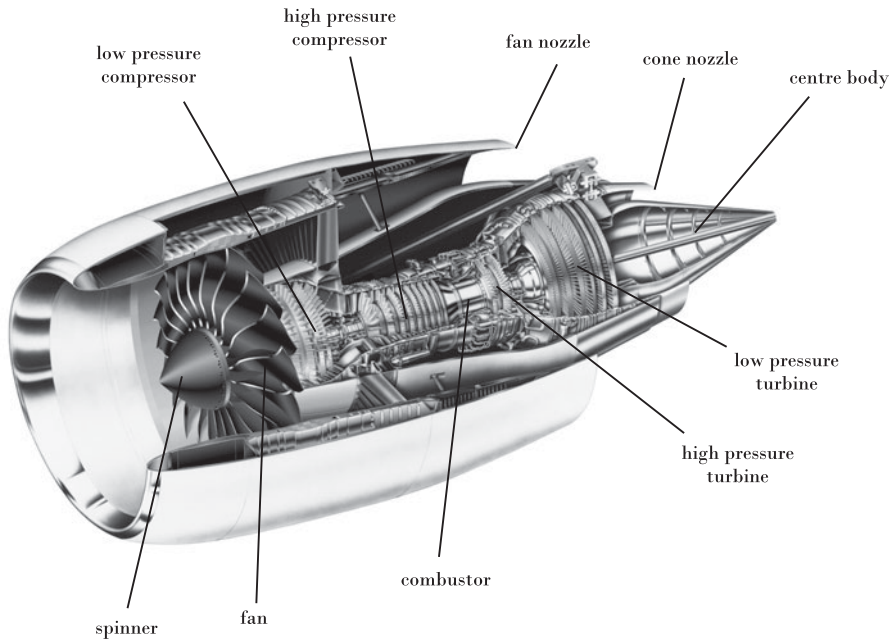
58 Frank R. Sample and Maurice E. Shank. 1985. Aircraft turbofans: new economic and environmental benefits. *Mechanical Engineering*, 107, 9, pp. 47-53; Michael S. Coalson, 'Jets fans', *Mechanical Engineering Supplement: 100 Years of Flight*, pp. 16-17, 38.

59 Pratt & Whitney, 'Pratt & Whitney's JT9D', http://www.pw.utc.com/StaticFiles/Pratt%20%20Whitney/Assets/Documents/commercial_2003_jt9d.pdf (consulted 11 March 2007).

60 Vaclav Smil, *Energy in nature and society: general energetics of complex systems*, Cambridge, MA: MIT Press, p. 375.

61 Details on the development of GE90-115B and its technical specifications are available at: Kyohei Horibe *et al.*, 'Development of GE90-115B turbofan engine', *IHI Engineering Review*, 37, 1, 2004, pp. 1-8, and at GE, 'Model GE90-115B', 2007, <http://www.geaviation.com/engines/commercial/ge90/ge90-115b.html> (consulted 12 March 2007). Engines made for superjumbo Airbus 380 are rated either at 374 kN (RR's Trent 900) or 363 kN (GP-7200, a joint GE and P&W product), both with 8.7 bypass ratio: Rolls Royce, 'Trent 900', http://www.rollsroyce.com/civil_aerospace/downloads/airlines/trent_900.pdf (consulted 11 March 2007).

Figure 2. An exploded view of a large modern gas turbine, GE's GE90-115 B, for powering wide-body jetliners. It shows the machine's main components. Image reproduced courtesy of General Electric Aeroengines in Cincinnati, Ohio.



exactly sixty-five times more powerful than was the world's first mass-produced turbojet, Franz's Jumo 004 in 1944, but needs less than a fifth of mass to develop the same power.

Fundamental innovations: origins, advances and longevity

Diesel engines epitomize that fascinating class of innovations that arise from the ideas of a single inventor and succeed largely because of the persistence of that highly dedicated individual. In contrast, the gas turbine had a tentative (and overwhelmingly theoretical) 'prehistory' (between 1890s and the late 1920s) and also then its practical realization was driven by two inventors who were not aware of each other's efforts. But the two prime movers share their origins in an innovative quest of independent inventors whose conviction and devotion were needed to overcome the scepticism, disinterest (and even outright scorn) of the established elites in their respective fields. The inventors had great, even noble, goals in their mind but they were not responding to any overwhelmingly felt need for such advances or racing to fill the expectations or demands of existing industries.

And the two prime movers also shared the course that followed the successful demonstration of their capabilities: their development became, fairly or very, rapidly a matter of focused innovative research and development conducted by major established companies in the two respective industries, MAN and Daimler Benz in the case of diesel engines, and Rolls Royce and Heinkel and Messerschmitt in the case of gas turbines. And, finally, they have a shared history of technical maturity: while their origins had nothing to do with

any existing commercial demand or expressed industrial need, their capacity growth and their efficiency improvements have taken place overwhelmingly in response to commercial pressures for better performance and lower costs.

And it is safe to conclude that they will share extended life spans. Prime movers, in common with the sources of primary energy (wood, coal, crude oil and natural gas), have relatively great longevity. When assessed on the global scale, coal was the world's most important source of primary energy supply between the late 1890s, when its worldwide extraction surpassed the aggregate energy content of biomass (wood, charcoal and crop residues), and 1964 when its output (in energy terms) fell below 50% of the total demand.⁶² The peak of the global extraction of conventional crude oil is very likely to be reached before 2020 and afterwards natural gas may become the most important fossil fuel in terms of its aggregate energy content. Consequently, spans of 50–60 years must be expected before a new primary energy resource asserts its global primacy.

Steam engines, commercially introduced on both trains and ships during the 1830s, dominated long-distance shipping between the 1860s and the 1930s before they were displaced by diesel engines. The Comet's short-lived history aside, commercial aviation relied solely on petrol-fuelled reciprocating engines from its inception during the early 1920s until 1957, and piston aircraft disappeared from long-distance flights during the 1960s. This means that diesel engines have already accumulated seven decades of prime mover primacy in intercontinental ocean transportation and that gas turbine aeroengines have entered their sixth decade of being the sole prime mover of long-distance flight. In either case there are no technically outstanding, commercially viable replacements on the near- to mid-term horizon.

Inherently low efficiency and hence a high rate of carbon emissions have raised concerns about the future of Otto-cycle internal combustion engines, and the candidates for a radical change range from hybrid designs (already commercialized) to all-electric cars, and from fuel cells to hydrogen-fuelled vehicles (still very far in the future). Similarly, there is an effort underway not only to produce much cleaner diesel engines powering passenger cars (particularly in Europe) and large trucks but to replace them with hybrid drives, fuel cells and gas turbines – but there are no such pressures on marine diesels. And while high prices of aviation fuel and carbon emissions from the expanding jet fleet will stimulate the continuing effort to design more efficient aeroengines and to introduce less carbon-intensive fuels, there is no candidate to replace gas turbine as the sole prime mover of long-distance flying.

Both of these cases thus provide important reminders that, contrary to often-voiced claims of an accelerating rate of innovation – there is now even an Institute for Accelerating Change⁶³ – many fundamental techniques are highly inertial in their basic conception even as they have undergone remarkable capacity and efficiency transformations. Tesla's induction motor and Parsons's steam turbine (both dating from the 1880s) are perhaps the other most notable examples of the persistence of prime movers, while Hall-Héroult's smelting of aluminum (also the 1880s) and the Haber-Bosch synthesis of ammonia, the world's most important synthetic compound (commercialized in 1913), are two outstanding examples of the same phenomenon as far as the two basic raw materials of modern civilization are concerned.

62 Vaclav Smil, *Energy in nature and society*, p. 375.

63 Institute for Accelerating Change (IAC), *Realizing the future of exponential promise*, Culver City, CA: IAC.

Moore's law, the most famous example of an admirable process of accelerating innovation, has cast a large, and distorting, shadow over the post-1970 notion of technical advances. When Gordon Moore formulated the law in 1965 he predicted that the number of transistors on a microchip would be doubling every 12 months and by 1972 a slightly slower pace led him to lengthen the period to approximately 18 months: nearly four decades later this norm is still with us.⁶⁴ But a closer look at the techniques that help to energize global civilization and that provide it with its prime movers and principal materials reveals that microprocessors (and by extension electronic devices in which they are installed) are exceptions to the norm: most of our fundamental technical patrimony is conceptually, and much of it even physically, three to six generations (60–120 years) old.⁶⁵

Most forecasts see further intensification of international trade and travel, and from the technical perspective there is little doubt that increasing capacities, higher efficiencies, lower costs and greater reliabilities of the two now clearly mature prime movers, diesel engines and gas turbines, could support continuing growth of seaborne shipments and aerial transports for decades to come. Whether they will be allowed to is a different matter: it is by no means certain that the economic, strategic, social, health and environmental costs of rampant globalization are having a net positive effect, and it would be ahistorical to assume that what now seems an unstoppable trend could not be substantially slowed down, even reversed, in the future.

Consequences, benefits and costs

There have been many obvious, as well as some not commonly appreciated, impacts of the two powerful, reliable and inexpensive prime movers on the global economic integration: the unprecedented growth of modernizing economies and the maintenance of an affluent life style in high-income countries. Consequently, it is no exaggeration to conclude that diesel engines and gas turbines have helped, in no small measure, to change the course of modern history. The most obvious effect has been the enormous increase in the mass of all internationally traded raw materials and finished goods; this trend has been accompanied and strengthened by declining costs of long-distance transport of goods; and this combination of huge volumes and low costs has virtually eliminated any concerns about the spatial origin of minerals or manufactures.

Not surprisingly, all of these changes have figured prominently in the world's most important bulk commodity trade, in international shipments of crude oil carried by large tankers. Their volume rose from less than 200 million t in 1950 to about 2.3 billion t by 2005,⁶⁶ shipping in a very large carrier is now less than half as costly as in the 50,000-dwt tankers

64 Gordon Moore, 'Cramming more components onto integrated circuits', *Electronics*, 1965, 38, 8, pp. 114–17; Intel., 2003, 'Moore's law', Santa Clara, CA: Intel., <http://www.intel.com/research/silicon/mooreslaw.htm>

65 Vaclav Smil, *Creating the twentieth century: technical innovations of 1867–1914 and their lasting impact*, New York: Oxford University Press, 2004; David Edgerton, *The shock of the old: technology and global history since 1900*, New York: Oxford University Press, 2007.

66 British Petroleum, *BP statistical review of world energy 2007*, London: BP. <http://www.bp.com/worldenergy>

of the 1950s,⁶⁷ and the resulting economies of scale and lower unit costs have essentially eliminated distance as an important consideration in buying crude oil: a delivery from another continent has become as affordable, and often more convenient, as a procurement from a neighbouring country. As a result, the United States, the world's largest importer of crude oil, now sources its purchases (and shipments of refined products) from seventy countries on four continents.⁶⁸

Identical trends could be illustrated by statistics for other commodities. Worldwide sea-borne exports of dry-bulk commodities increased from 900 million t in 1980 to more than 1.5 billion t by 2005: coal, with more than 700 million t, iron ore, with more than 500 million t, and grain (about 250 million t) are the leading cargoes.⁶⁹ Irrelevance of distance is illustrated by the fact that English coal-fired power plants now get most of their coal from Australia, Colombia, Indonesia and South Africa:⁷⁰ now it is not only coals to Newcastle, but to Newcastle from the antipodes, with 2006 coal imports twice as large as domestic production and at a cost lower than coal from the Midlands.

As for the factory goods, nothing illustrates the impact of inexpensive containerized diesel-powered shipping more impressively than the post-1990 emergence of China as a new manufacturing hub of the world: it is irrelevant whether the goods are made of locally produced cheap raw materials (daily wear apparel or toys) or if they are assembled from expensive components that are imported from other countries (electronic devices ranging from cellphones to laptops), and it does not matter if they are destined for exports within Asia or to North America and Europe. The combination of China's low-cost and disciplined, flexible and non-unionized labour is the primary factor for locating the factories; the cost of shipping is not even a secondary consideration.

As a result, Chinese exports have more than quintupled between 1995 and 2005, from \$148.8 billion to \$762 billion.⁷¹ They have made Hong Kong, Shanghai and Shenzhen, respectively, the world's second, third and fourth busiest container ports of origin (Singapore, thanks to transshipments, became number one in 2005); Rotterdam, Los Angeles, Long Beach and Hamburg are the busiest receiver ports. In 2005 Singapore handled 23.2 million TEU, Hong Kong 22.6, Shanghai 18.1 and Shenzhen 15.6; major Chinese ports (including Hong Kong) handled 81.1 million TEU in 2005, or about 27% of the global total.⁷²

And there is an important additional reason why the term revolution is not hyperbolic when describing the reality of the post-1950 impact that large diesel engines had on ocean

67 Takeshi Izuta, *Progress in marine transportation*, Tokyo: Taiyo Shosen Kaisha, 1967, pp. 19.

68 US Energy Information Administration, *U.S. imports by country of origin*, Washington, DC: EIA, 2007, http://tonto.eia.doe.gov/dnav/pet/pet_move_impcus_a2_nus-ep00_im0_mbb1_m.htm (consulted 2 August 2007).

69 World Coal Institute, 'Coal facts 2006 edition', 2007, <http://www.worldcoal.org/pages/content/index.asp?PageID=188> (consulted 13 March 2007); Christel Heideloff and Dieter Stockman, 'ISL market analysis 2005: major shipping countries', *Shipping statistics and market review*, 10, 2005, pp. 3–6.

70 Department for Business Enterprise and Regulatory Reform, *Coal industry in the UK*, 2007, <http://www.dti.gov.uk/energy/sources/coal/indsurty/page13125.html> (consulted 3 August 2007).

71 National Bureau of Statistics, *China statistical yearbook*, Beijing: China Statistics Press, annually.

72 Christel Heideloff and Dieter Stockman, 'World seaborne container trade and port traffic', *Shipping statistics and market review*, 6, 2006, pp. 1–5.

shipping. These shipments are not only voluminous and inexpensive but also very fast and highly reliable. At the beginning of the twentieth century small (typically 5,000–6,000 dwt) general purpose cargo ships – powered by bulky and inefficient coal-fired steam engines and loaded and emptied by time-consuming, and only partially mechanized, labour – travelled at about 15 km/h. In contrast, the largest container ships have to adhere to taxing schedules (some constantly shuttling between two ports, others plying complex multi-stop routes connecting several continents) as their powerful diesels propel them at speeds of up to 46 km/h.

Moreover, modern cargo ships can be loaded and offloaded about twenty times faster than their counterparts in 1950 – by cranes that are themselves often powered by diesel engines. Straddle carriers and reach stackers (used to deposit and remove containers prior to further land shipment) are also commonly powered by diesel engines, as are, of course, large trucks and long container-carrying trains that take the containers to their final inland destinations. Clearly, no other modern technique has contributed as much to the globalization of trade and to the rise of economic interdependence. In global terms this cause-and-effect relationship between the more powerful, more efficient, more reliable and more affordable prime movers and the accelerating progress of international trade is perhaps best illustrated by the fact that the growth rate of the maximum size of container ships (since their conception in 1956 to 2006) has been closely replicated by the expansion of manufactured exports that now move (with the exception of cars) solely in containers. But it would be a case of indefensible technical determinism to see this all as merely a one-way cause-and-effect process.

Neither diesel nor jet engines were invented in order to fill some waiting market niche and the early stages of their development have met with a less than enthusiastic acceptance by the established commercial leaders of the two respective fields. But, fortuitously, the commercial maturity of both engines had almost perfectly coincided with the post-Second World War emergence of new, much more open, economic structures that were promoted first by the US relations with Western Europe and Japan and later by a worldwide progress toward a freer trade. The two efficient prime movers found new and rapidly expanding niches in an increasingly interconnected world (giant crude oil tankers, container ships, wide-body jets) and the rising demands for long-distance transport of goods and for personal travel created strong incentives for a further enhancement of their capacities and efficiencies as well for their more durable and safer performance. Naturally, all of these qualities would have mattered much less in the more autarkic pre-Second World War world.

Consequently, many non-technical factors of the past two generations – ranging from the substitution of coal by crude oil to the guarantee of safe shipping routes provided by US naval power, and from rising disposable incomes in North America as well as in the newly reconstructed economies of Japan and Western Europe to the steadily broadening scope of free trade agreements – have coalesced to stimulate the technical progress of the two prime movers. Globalization of trade and travel and the post-1950 development of diesel and jet engines have constituted a reciprocal and complementary process in which these two remarkable machines have played *primae inter pares* roles.

And, for the first time in history, this trade is now making a truly global difference. Even as recently as 1950, worldwide exports amounted to less than 2% of the gross world product (GWP); by 1975 their share was almost 6% – but by the year 2000 it reached 15%

and further strong growth lies ahead.⁷³ This new web of economic integration has brought immense benefits first to Japan and smaller East Asian economies (South Korea, Taiwan, Hong Kong), and, as already noted, since the early 1990s it has been the key factor behind the rise of China, the world's new manufacturing superpower, as well as behind the reinvigorated growth in India.

At the same time, the mass influx of inexpensive (but increasingly high-quality) consumer goods has benefited the importing countries, above all by keeping inflation in check for nearly a generation – even as it has brought large job losses in diverse manufacturing industries. These contrasting impacts have been perhaps best exemplified by the dependence of America's Wal-Mart, the world's largest retailer, on China's manufactures and by the concurrent loss of manufacturing jobs in the United States. The best estimate is that in 2006 Wal-Mart sourced at least 80% of its worldwide sales from China (with virtually all of these products shipped in containers) and that these imports have displaced nearly 200,000 US jobs, while the net jobs lost to all Chinese imports had displaced 2.76 million US jobs between 2001 (when China joined the World Trade Organization) and 2006.⁷⁴

Higher power and the more efficient, and more reliable, performance of gas turbines used to power large commercial jets have been impressively reflected in the exponential growth of the world's airline traffic. This aggregate rose roughly 15-fold during the 1930s to almost 1.5 billion passenger-kilometres (p-km) in 1939. By 1950 it was at 28 billion and then its doubling time of less than six years produced a 100-fold increase to nearly 3 trillion p-km by the year 2000. Although it seemed inconceivable at that time, even the tragedy of 9/11 had a surprisingly small impact as the total rose by another 25% to surpass 3.7 trillion p-km in 2005 when, for the first time, airlines carried more than two billion passengers a year, 35% of them on international routes.⁷⁵ Another revealing indicator of globalization induced by flying is the falling share of the world market held by the previously US companies: in 1950 they accounted for more than 80% of all p-km, and still claimed half of the global total during the late 1960s, but by 2005 their share was down to 33%.⁷⁶

And while only a tiny minority of frequent fliers may be aware of these performance statistics and have some understanding of continuous technical improvements of gas turbines, most passenger have become aware of the extraordinary high reliability of large turbofans, which has made commercial flight the safest mode of public transport and has transformed globe-spanning travel from an exceptional event to a routine experience. In 1950 (with piston aircraft only) there were 1.97 fatalities per 100 million passenger-kilometres (p-km); by 1965 (with the first generation of turbojets) the rate was down to 0.35 and in 2005 it stood at just 0.02; accidents measured per million of departures for scheduled commercial flights were in excess of 50 in 1960 but they averaged just 0.89

73 Calculated from data in World Trade Organization, *International trade statistics 2001*, Geneva: WTO, 2001, pp. 29–30.

74 Robert E. Scott, *The Wal-Mart effect*, Washington, DC: Economic Policy Institute, 2007.

75 ICAO, 'Special report: Annual review of civil aviation', *ICAO Journal*, 61, 5, 2006, p. 10.

76 ICAO, 'Special report', p. 12.

between 1996 and 2005, with less than 5% of this very low total attributable to system or component failure or malfunction of engines.⁷⁷

Another consequence of this reliability has been a routine use of twin-engine aircraft (mainly Boeing 757, 767 and 777 and various Airbus planes) on routes where they are up to three hours from the nearest airport (this means not only on trans-Atlantic routes but also on all northerly trans-Pacific routes), and since 15 February 2007 qualified aircraft can fly oceanic and polar routes without any range restrictions whatsoever.⁷⁸ The more powerful turbofans have also become considerably cheaper to operate and both travellers and the airline companies care about the cost of flying, so this decline in specific costs has been the single most important factor in transforming long-distance flight from a rare experience to a ubiquitous mass action. Gas turbine efficiency was 15–18% for the first generation of turbojets of the late 1950s; it rose to 20–25% for low-bypass ratio turbofans of the 1960s and to 28–32% for the high-bypass ratio turbofans of the 1980s. Currently the best performance is at about 36% and engines with 40% efficiency are under development.⁷⁹

And (as any frequent flier knows by watching the huge crates loaded into the aircraft holds), every long-distance passenger plane is also a cargo plane (this service accounts for 10–15% of total revenue), every major airline has special cargo carriers, and there are many specialized cargo companies. Wide-body aeroplanes usually carry 10–20 t of containerized cargo on long-distance flights while cargo planes transport 50–100 t. In addition to such well-known commercial cargo fleets as FedEx or UPS, there are many specialized charters that serve the global economy, as well as the global-reach military. The Boeing 747 is the most common international cargo carrier but the Soviet-designed and now Ukrainian-produced Antonov-124 (*Ruslan*) can carry nearly 50% more (up to 150 t) and it has been used to transport anything from heavy oil-drilling equipment to armaments for peacekeeping operations around the world.⁸⁰ Global air cargo services totalled only about 750 million tonne-km (t-km) in 1950 but by the year 2005, when they carried nearly 38 million t of freight, they were more than 140 billion t-km (nearly a 200-fold increase) with nearly 90% of the total on international routes.⁸¹

In personal and social terms, inexpensive intercontinental flights have accelerated the worldwide movement of (legal and illegal) migrants, made it possible to maintain family ties and opened up unprecedented opportunities for journeys of leisure or private

77 International Civil Aviation Organization (ICAO), 'Civil aviation in 1969', *ICAO Bulletin*, 25, 5, 197, p. 46; Boeing, *Statistical summary of commercial jet airplane accidents: worldwide operations 1959–2005*, Seattle, WA: Boeing, 2006.

78 John Croft, 'US FAA to end ETOPS range restrictions for qualified aircraft', Flightglobal.com, 9 January 2007, <http://www.flightglobal.com/articles/2007/01/09/211460/us-faa-to-end-etops-range-restrictions-for-qualified.html> (consulted 13 March 2007). This means that airlines can choose fuel- and time-saving direct routes that will put twin-engine planes more than three hours from the nearest airport during a part of their journey.

79 B. L. Koff, 'Spanning the globe with jet propulsion', Arlington, VA: American Institute of Aeronautics and Astronautics, 1991, p. 2; Joosung J. Lee *et al.*, 'Historical and future trends in aircraft performance, cost, and emissions', *Annual Review of Energy and Environment*, 2001, 26, pp. 167–200.

80 Volga-Dnepr Airlines, headquartered in Ulyanovsk, is Russia's, and the world's, leading provider of outsize and heavy global airlift using its 10 Antonov-124 planes; since 1990 it has served clients ranging from UN to NATO, and from Exxon to Airbus. See <http://www.volga-dnepr.com/>

81 ICAO, 'Special report', p. 10.

discovery – even as they expanded and aggravated the problems of illegal migration, organized crime, drug trade and international terrorism. Given the makeup of the world's current and future population it may take generations before we will not have to associate flying with terror. To this list of concerns must be added rapid intercontinental transmission of infectious diseases, a reality that has already been so dramatically illustrated by the diffusion of SARS from Hong Kong to Toronto⁸² and whose much more dangerous reprise has been so anxiously anticipated in the case of a new influenza pandemic, a fear that is justified by the fact that the annual flu epidemic is clearly spread by air travel.⁸³

Yet another negative impact has been the worldwide diffusion of invasive species facilitated by both maritime and air travel. A notable example of such an invasion has been the introduction of European zebra mussels that were carried in ballast water to North America and took hold in Ohio and Michigan in 1988: they have now penetrated all of the Great Lakes and the Mississippi basin, their massive colonies cloak and clog underwater structures and pipe inlets, reduce the presence of native mussel species, and cause economic damage in billions of dollars per decade.⁸⁴ The Asian longhorned beetle has been perhaps the most unwelcome recent introduction to North America from Asia; carried in wooden packing crates from China, there is no known defence against its introduction short of cutting down the infested trees.⁸⁵

But globalization, regardless of the performance and cost of its prime movers, has its obvious physical limits. The peak of global oil extraction may not be just years away as is anticipated by some geologists, but it is very likely to come by 2020 or 2030.⁸⁶ Long before it arrives it will be signalled by increasing crude oil prices (this shift may have already started) that will make kerosene and diesel fuel significantly more expensive and all long-distance shipments much less rewarding. Dependence on distant markets, particularly in the case of foodstuffs, has already led to increased concerns about the safety of supplies and to calls for returning to a greater reliance on locally or regionally produced food.⁸⁷ Should the real costs of refined liquid fuels triple or quadruple, it will hardly make sense to ship out-of-season fresh fruit (containing more than 90% water) to distant continents

82 Thomas Abraham, *Twenty-first century plague: the story of SARS*, Baltimore, MD: Johns Hopkins University Press, 2005.

83 John S. Brownstein *et al.*, 'Empirical evidence for the effect of airline travel on inter-regional influenza spread in the United States', *Public Library of Science Medicine*, 2006, 3, p. 10, doi:10.1371/journal.pmed.0030401

84 US Geological Survey, 'Zebra mussels page', 2007, <http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/> (consulted 15 March 2007).

85 A. T. Peterson, R. Scchetti-Pereira and W. W. Hargrove, 'Potential geographic distribution of *Anoplophora glabripennis* (Coleoptera : Cerambycidae) in North America', *American Midland Naturalist*, 2004, 151, pp. 170–8.

86 Vaclav Smil, 'Peak oil: A catastrophist cult and complex realities', *World Watch*, 2006, 19, pp. 22–4. R. A. Kerr, 'The looming oil crisis could arrive uncomfortably soon', *Science*, 316, p. 351.

87 This movement embraces such diverse strands as slow food (for its programmatic statement see: 'Il manifesto dello slow-food' http://editore.slowfood.it/editore/riviste/slowfood/IT/19/articoli/slowfood19_05.pdf), eco-agriculture, seasonal eating and resurgent farmers markets. The case for local food is made by Brian Halweil, *Eat here: reclaiming homegrown pleasures in a global supermarket*, Washington, DC: Worldwatch, 2004.

and, because people expect the fruit to arrive unblemished, spend more energy on cooling it along the way.

The power of global business, disappearance of cherished traditions and a complete dominance of entire market segments by products from other continents have all combined to lead to resentment, local opposition and nationalistic feelings; the reactions that often accompany sudden interactions of strangers and whose political and social consequences should not be underestimated. A perfect example of an already accomplished major change in intercontinental shipping is the case of Japanese car exports to the US. Because of the American resentment of large Japanese trade surpluses during the 1980s all Japanese auto-makers decided to manufacture in the US and Canada most of the cars they sell in North America: most of the profits still go across the ocean but millions of cars no longer do.

As far as flying is concerned, the existing arrangements (airport terminals, runways, control systems, landing rights, security) cannot meet even today's demand, resulting in an unprecedented share of delayed and cancelled flights and in compromised safety. Given this reality, it is difficult to envisage a several-fold increase in the overall passenger count without massive new investment and major technical fixes – but neither appears to be imminent. And, again, a drastic increase in the cost of kerosene would inevitably curtail the frequency of both business and discretionary flying. The air industry also provides a perfect example of the limits of corporate globalization. There are only two makers of large commercial planes (Boeing and Airbus) and two makers of small (regional) jets (Canadair and Embraer) and powerful national and anti-trust interests will prevent the creation of monopolies in either sector: clearly, this globalization process has reached its limit.

Expectations created by rising globalization of trade and travel are both understandable and problematic. Affluent consumers (and richer urbanites in low-income countries), now take it for granted that basic manufactured goods should be fairly inexpensive (and in terms of average purchasing power actually progressively cheaper) and that they should have access to an unprecedented range of foodstuffs and products. And the producers of these goods for distant markets (be they the Chinese assemblers of toys and laptops or Chilean or South African growers of grapes and pears) have come to expect that their output will continue to be in demand in ever greater quantities. Leisure and business trips on an intercontinental scale have become routine for hundreds of millions of travellers, resulting in previously unthinkable personal experiences and productive ventures – and, again, airlines anticipate further large increases of their aggregate passenger and cargo capacities. Beneficiaries of the process expect its rewards to continue – but they do not appreciate how fragile this arrangement is and how impermanent it may turn out to be in the long run.

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