Fifty-five years ago, 'What Price Speed?' illustrated the price to pay in terms of efficiency for faster travel. Now Imperial College's Railway Research Group updates this seminal study and shows that the efficiency range of modern transport modes has been 'stretched' at both ends. Economic and environmental demands leading to more efficient transport have been matched by a growth in faster, more fuel hungry modes brought about by society's need for speed.

WHAT PRICE SPEED – REVISITED

THE DEVELOPMENT OF TRANSPORT

As society grows wealthier over time, people tend to travel more frequently and over greater distances. Travel demand increases by a factor of approximately 10 for each generation, but the amount of time spent travelling has remained constant at approximately one hour per day per person over the past three decades. The primary reason for this is the development of faster and faster modes of transport. Speed is a key driver for transport developments, although factors such as price, convenience, comfort and safety also play major roles.

'WHAT PRICE SPEED?'

Transport now consumes a large and increasing proportion of our energy budget. Efficient energy use is therefore of considerable importance, but a method of comparison over a wide range of speeds and different vehicle types is by no means obvious. In a classic paper written just over 50 years ago, Gabrielli and von Kármán suggested using specific traction force (or conversely specific resistance) to make such comparisons. The central question of their paper was 'What Price Speed?'. A further examination of this revealed that any form of transport is an economic balance between the cost of the transport and the value of the time that goods or people are incapacitated for during transit. As Gabrielli and von Kármán also predicted travel trends 50 years into the future, it is now opportune to revisit and update their work.

SPECIFIC TRACTIVE FORCE

For any vehicle type, motion is achieved through the action of a tractive force, which is the ratio of power (*P*) divided by velocity (*V*). If this ratio is further divided by the weight (*W*) then the non-dimensional specific tractive force ($\mathcal{E}$) is obtained ($\mathcal{E}=P/WV$). This can also be interpreted as the specific resistance, akin to a coefficient of friction. The lower the value, the more 'efficient' the transport mode.

Gabrielli and von Kármán assembled a collection of data for installed power, maximum velocity and gross weight for a wide variety of transport modes. Their original data, transformed to SI units, is shown in Figure 1, in which $\mathcal{E}$ is plotted as a function of speed. Broadly speaking, sea, land and air transport are divided into bands of $\mathcal{E}$ from 0.001 to 0.01, between 0.01 and 0.1 and greater than 0.1 respectively. The bulk of the data lies above a line of gradient 1, identified as the Gabrielli-Kármán (GK) line, which represents 'best performance'. The only exceptions below

the line are varieties of railway vehicles which operate using a convoy system, for which the resistive force does not increase appreciably with the length of the train (see Figure 1).

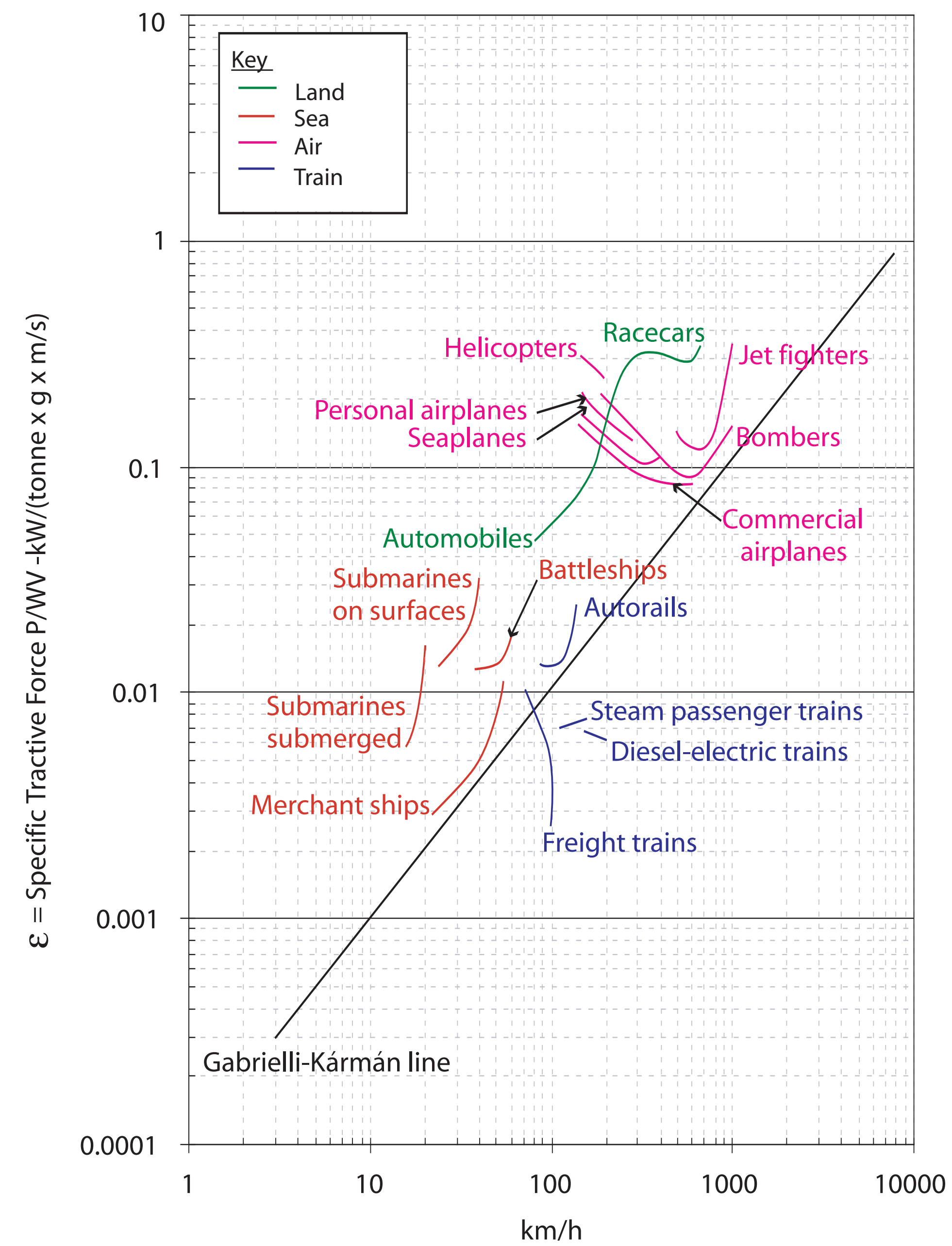

Figure 1
Specific resistance for various transport modes before 1950. The Gabrielli-Kármán (GK) line represents best performance.

MODERN VEHICLES

The Railway Research Group at Imperial College, London has recently updated this with information about modern vehicles (with the exception of military vehicles) as shown in Figure 2. At first sight, the fruits of 55 years endeavour seem slight, but the representations are on logarithmic scales, so careful interpretation is needed. Increases in speed will push data to the right, whilst higher speeds need more installed power, which pushes data upwards. On sea, land and air, the best performance has now moved below the original GK line (movement emphasised by arrows on Figure 2), illustrating considerable performance improvement in all kinds of transport. For each of the various transport modes, a line is drawn to represent the lower boundary of existing vehicles. In general, existing technology is capable of producing a vehicle that resides to the left and above the boundary, but some sort of technological advancement is required for a new vehicle to surpass the line and add a data point to the lower-right. A look at the improvements for each mode of transport follows.

AIR TRANSPORT

The jet engine has been one of the most significant developments in aircraft propulsion. Combined with a huge increase in the size of aeroplanes, it has enabled a huge growth (and democratisation through lower fares) of air transport to occur over the last 55 years. The Boeing 747-400 ER, with a maximum cruising speed of approximately 1020 km/h and a maximum seating capacity of 524, is an example of a modern plane below the original GK line. Its four engines produce a combined power of about 78 MW at cruise. By comparison, 55 years ago a trans-continental train would have operated at 100 km/h with about 1 MW of steam power.

Developments in material technology have enabled power to weight ratios to increase, through weight reduction in power plants, structure and internal fittings. Together with improvements in combustion technology, the changes have resulted in a huge increase in the operational range of commercial planes. The longest single-leg flight now available is from Singapore to New York, a great-circle distance of 15,323 km

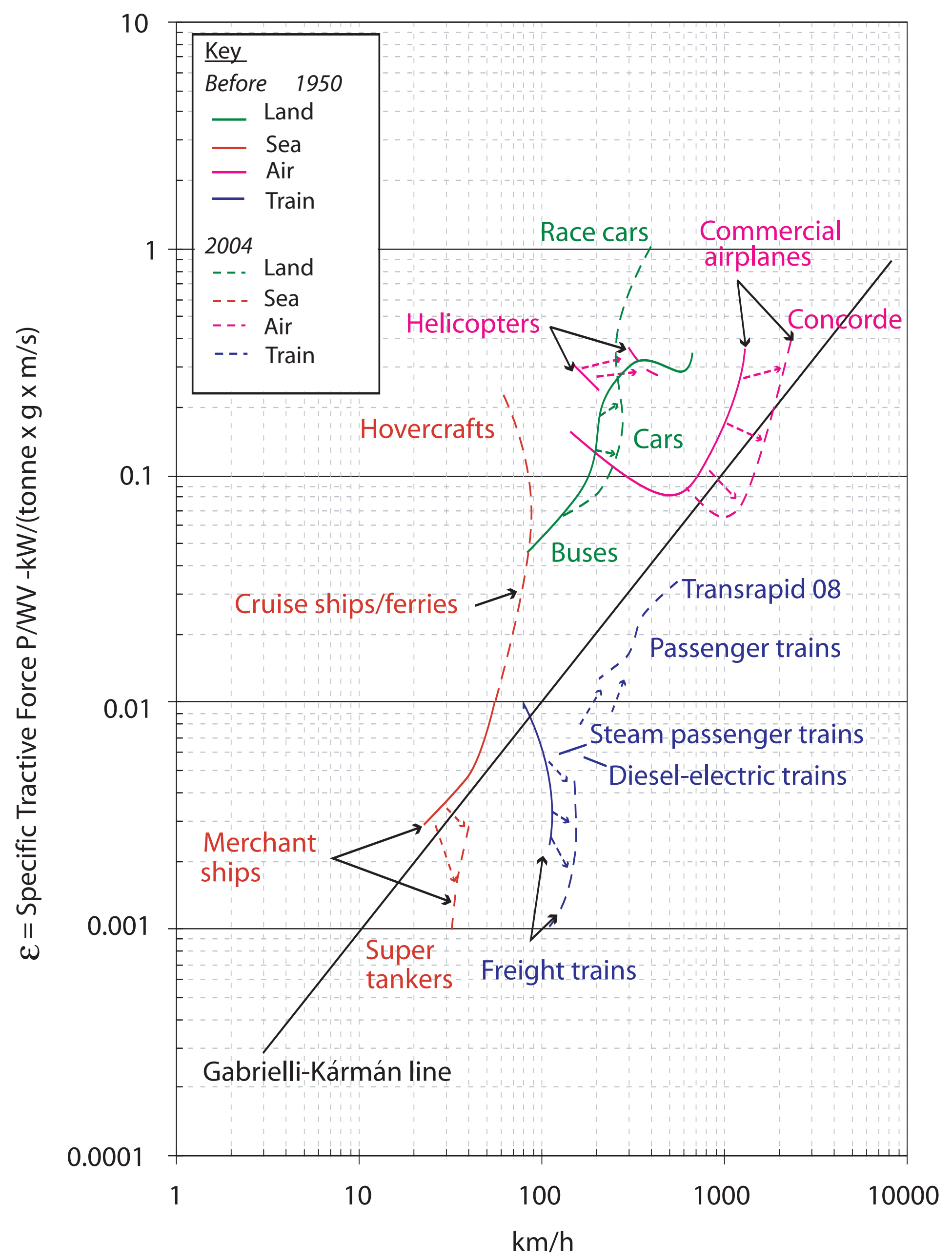

Figure 2
Updated specific resistance of various transport modes (with exception of military vehicles) over the last 54 years. The data lines for sea, land and air transport have moved below the original GK line (movement illustrated by arrows), which illustrates considerable performance improvement in all kinds of transport.

covered in 18 hours. Fifty-five years ago, this journey would most likely have been made by ocean liner. At take-off, most of the weight carried by the aeroplane is fuel, thus the reduction in structural weight per passenger has enabled an increased fuel load.

Gabrielli and von Kármán's original paper was written at a time that marked the dawn of commercial air transport. Even then however, they noted that successful air transport relied upon aircraft travelling at high speed and at a high altitude. Modern aircraft have confirmed this, and fly at an optimum height of approximately 10,000m. At this height the air temperature drops to about -50ºC and stabilises above this height. Flying higher than this would not produce a further gain in the thermal efficiency of the combustion process. Also, at 10,000m aircraft fly above the 'weather' and are therefore able to take advantage of the jet stream.

Airfreight was not recognised by Gabrielli and von Kármán as feasible because of the then high cost associated with air transport. It is evidence of the success of air transport that there is now a buoyant market for the transport of relatively high value goods across the world as airfreight. Supersonic commercial flight has been both introduced and withdrawn in the last 30 years. Concorde, the fastest mode of transport shown on Figure 2, was some way above the GK line. Its demise was probably the first time that a major advance in transport technology has been successfully introduced into service, but subsequently withdrawn on economic and environmental grounds. Back then, speed was the driving force for Concorde's development – a stark contrast to the higher capacity and lower costs that underpin the rapid growth of today's commercial aircraft industry and the recent rise of budget airlines.

TERRESTRIAL TRANSPORT: RAILWAYS

It has already been noted that the 'convoy' system gives trains some advantages as most of the resistance is generated by the front of the train and little more is added as the length of the train increases. In the 55 years since Gabrielli and von Kármán's paper, steam traction (aside from some small pockets) has been superseded, with diesel or electric power replacing coal. Fifty-five years ago it was thought that the age of the train itself was coming to an end, but today more passengers and freight in total are carried on the world's railways. The most striking development has been that of high-speed passenger trains, which have pushed speeds up from 100 km/h to 300-350 km/h, and challenged the dominance of aircraft over journeys of up to 3–4 hours in Japan and Western Europe. These high speed trains perform below the original GK line, and as many technologies from the aircraft industry have been adopted by the railways, performance has improved even at low speeds. Where freight trains are longer and have a greater payload capacity, commuter trains are faster and lighter; the latter improvement stemming from development in power electronics and improved power/weight ratio and size of electric motors.

CARS

In recent years there has been an increasing emphasis on improving the efficiency of road vehicles, partly because of concerns about fuel price and the widely-publicised impact of global warming. Attempts by manufacturers to reduce automobile weight have been hindered by the installation of items such as air conditioning, heating and air bags. Today, cars are more streamlined than their predecessors in order to reduce aerodynamic drag and hence improve the fuel consumption. The development of automobiles has seen the introduction of smaller, more efficient engines which emit less pollution and have lower fuel consumption. The most common type of engine remains the internal combustion engine powered by hydrocarbon fuel. Electrical hybrids have started to appear, but the absence of technology enabling us to store electricity compactly means that the all-electric car is still not feasible.

The use of hydrogen to power the internal combustion engine and/or a fuel cell is being investigated by nearly all of the major car manufacturers. There are still numerous technical hurdles to overcome, but through engineering innovation these issues are being resolved rapidly. Optimistic estimates suggest that the commercial introduction of this technology is but a decade away.

Shinkansen 500 Series Courtesy of Roderick Smith

HEAVY GOODS VEHICLES

The structure of modern light trucks and lorries does not differ greatly from those of 50 years ago, although there are more vehicles in use today. Modern trucks generally have a more streamlined front cabin and body to reduce the aerodynamic drag. However, the payload of trucks has increased substantially through the development of more efficient and powerful engines. In 2001 the UK government introduced new legislation to raise the maximum weight for articulated lorries to 44 tonnes (a maximum of 10.5 tonnes per axle), provided that the lorries have 6 axles to carry the weight. Prior to the release of the legislation, an extensive consultation showed that a move to 44 tonne lorries would save lorries 100 million km every year, with consequent reductions in congestion, emissions and road wear, a factor consistent with the government's sustainable transport strategy.

WATER TRANSPORT

Marine design made rapid strides under the stimulus of World War II with traditional riveted construction giving way to welding. When the war ended in 1945 many larger and more advanced ships were built worldwide. The closure of the Suez Canal gave rise to the giant Cape tanker and small merchant ships were replaced with bulk carriers and container ships. These bigger ships suffer proportionally less drag and are able to cruise very efficiently and economically, far below the GK line. This is extremely important because the world's economy depends on the huge volume of goods transported by sea. The tonnage involved far exceeds that of all other transport modes combined, a fact often overlooked because of the 'out of sight' nature of the shipping process.

Although the passenger liner has been superseded by the aeroplane, passenger ferries are still important and, again, have greatly increased in size, capacity and efficiency. For example, the recently constructed Queen Mary II luxury cruise liner is the largest ever built, with a deadweight of 14,300 tonnes and full displacement of 79,461 tonnes. As for bulk carriers, the Hellespont Alhambra, the ultra-large crude carrier (ULCC), is capable of carrying more than 441,893 tonnes deadweight.

VLCC Hellespont Alhambra Courtesy of The Royal Institution of Naval Architects

Airbus A380: One of the few aircraft which surpasses the GK line © Airbus SAS

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Not only have the size of ships grown, the installed power has also increased, thanks to the incremental succession from steam to diesel engines and gas turbines. Whilst the nuclear reactor has only been employed in military submarines and ships, the diesel engine is by far the most efficient of the propulsion machinery options open to commercial ship designers, with thermal efficiencies of 43%, followed by 35% for gas turbines and 20% for steam turbines. Recent research has demonstrated that fuel cells could also be used in marine propulsion in the future.

IMPLICATIONS FOR THE FUTURE

Many of the successful developments in transport over the last 55 years have been of an incremental nature, with improvements being made in aeroplanes, trains and large merchant ships in particular. Some radical step changes in transport have been unsuccessful, for example Concorde, hovercraft and the electric car (so far). Predictions are difficult to make, but there is no obvious candidate for a new transport mode that will revolutionise our lives.

The challenges presented by climate change are likely to have a great impact on transport developments. Whilst the damage inflicted by the rapid expansion of car use is well appreciated, the harm caused by the growth in air traffic is only just being understood. The search for sustainable transport will also almost certainly create the need to develop more attractive and flexible forms of public transport, since a high load factor in multi-occupancy vehicles automatically produces better returns of fuel consumption per passenger per kilometre.

As a significant consumer of the world's finite hydrocarbon reserves, transport will be poorly equipped to deal with the uncertainty of future supplies. Oil production is approaching an inevitable peak, and when this is reached the fuel prices will escalate. Returning to Gabrielli and von Kármán's question 'What Price Speed?' it seems that the cost of providing transport will eventually increase, especially if externalities are taken into account, and a host of technological advancements will be necessary to permit our extensive use of transport and to ensure continuing economic growth.

There will almost certainly be a steady incremental improvement in materials technology which will continue to produce vehicles which surpass the GK line. Transport will also be significantly influenced by political and economic decisions. If there is a serious attempt to radically reduce the emissions of CO_2, then transport using hydrogen for power will be the most attractive option. Most of the hydrogen used today is reformed from natural gas. This process produces CO_2, but the technology now exists which can, at moderate cost, capture the CO_2 which can then be safely stored long-term in disused oil fields. Hydrogen, then, has the potential to be virtually CO_2 free. In the longer term, nuclear fission, fusion and renewables, would provide the energy for the direct electrolysis from water. The assessment of the feasibility of hydrogen for air, land and sea transport is currently receiving attention in a number of research projects worldwide.

In summary, it is likely that these modes of transport will remain unchanged in the coming decades, albeit with some modest improvements. Speed will not be pursued at any cost, and the change to a hydrogen-powered transport system seems inevitable. The process will almost certainly be gradual, and yet there remains a degree of uncertainty as to the impact and timescale of these future developments.

Further reference

G Gabrielli and T von Kármán *'What price speed? Specific power required for propulsion of vehicles'*, Mechanical Engineering, ASME, Volume 72, Number 10, (1950), p775–781

BIOGRAPHIES – Janet Yong, Rod Smith, Linda Hatano and Stuart Hillmansen

Janet Yong, Rod Smith, Linda Hatano and Stuart Hillmansen are members of the Railway Research Group in the Department of Mechanical Engineering of Imperial College London. Their principal expertise lies within structural integrity analysis, and the group have been involved in the investigations of recent structural integrity failures which have led to train derailments. Ensuring the future sustainability of the railway is also a key objective for the group, which is being achieved by benchmarking international railways and identifying best practice, and by assessing the current environmental performance of the railway.