# FUNDAMENTALS OF PROPULSION

## PROPULSION

Propulsion (Lat. *pro-pellere*, push forward) is making a body to move (against natural forces), i.e. fighting against the natural tendency of relative-motion to decay. Motion is relative to an environment. Sometimes, propulsion is identified with thrust, the force pushing a body to move against natural forces, and one might say that propulsion is thrust (but thrust not necessary implies motion, as when pushing against a wall; on the other hand, propulsion implies thrust).

Sometimes a distinction is made from propulsion (pushing) to traction (pulling), but, leaving aside internal stresses in the system (compression in the first case and tension in the latter), push and pull motions produces the same effect: making a body to move against natural forces. In other occasions 'traction' is restricted to propulsion by shear forces on solid surfaces.

The special case of creating aerodynamic thrust to just balance gravitational attraction of a vehicle without solid contact (e.g. hovering helicopters, hovering VTOL-aircraft, hovering rockets, hovering hovercraft...), is often included as propulsion (it is usually based on the same engine), though its propulsion efficiency is zero.

Propulsion may be wanted for:

- Travel, i.e. the movement of people between different locations (personal mobility), with purpose of exploration (adventure, science, pride...), pleasure (tourism), commercial (business), military...
- Transport of goods (and, by extension, of people). Transport can be split in two classes:
    - Vehicular transport, where goods (or people) are taken in batch, usually in a self-powered vehicle (but sometimes in cable-drawn vehicles), with or without a crew (with local automatic pilot, or remote human control).
    - Continuous transport of goods, e.g. the propulsion of fluids or solids using pipes and ducts (closed or open), conveyor belts, pneumatic tubes, etc. We no longer deal with this topic here.
- Sending objects far away, e.g. from throwing a stone in defence or attack, to landing a robot in Saturn's moon Titan. We can include here all kind of unmanned vehicles and thrown weapons.
- Keeping objects hovering against gravity by the vehicle propulsion system (distinct to externally-applied levitation).
- Braking, i.e. the accelerated and controlled stop of a vehicle. This is always the case in space propulsion under vacuum, but on ground there are more efficient ways, like increasing friction in wheel-to-ground contact, or increasing ambient-fluid drag, although the latter is only efficient at high speeds, and another way must be applied at low speeds to finally keep the vehicle at a fixed position (static friction forces and wedges in wheel-to-ground contact, mooring and anchoring in ships and airships, or dynamic positioning using the propulsion system).

The major application of propulsion is for transportation of people (passengers, shorthanded to 'pax') and goods (usually measured in tonnes, t), over land, sea, air, undersea, and into space. Travel has traditionally been a passport to knowledge, discovering new horizons, new landscapes, new people, with unexpected personal and social achievements… the wonders of the world. Public transport started in waterways in Antiquity (land transport was on foot or horseback), and the first stagecoach, traveling a fixed route between coaching inns, dates from early 1600. The first organized public transit system within a city was stablished by Blaise Pascal in Paris in 1662, but it only lasted a few years due to increasing administrative regulation. Widespread use of public city transport started in Nantes in 1826 with the Omnibus (dative plural of Lat. *omnis*, all), and in London in 1829.

A transportation mode is the ensemble of a vehicle type, its infrastructures, and its operation particulars (e.g. loading and unloading procedures, traffic regulations...). To quantify offer, demand, and cost in transport business, two combined units are widely used: 'pkm' and 'tkm'; pkm stands for 1 person times 1 km (i.e. 1 pkm=1 pax·km), and tkm stands for 1 tonne times 1 km (sometimes the 'kgkm' unit is used for a simpler metric unit, and 'pmi' for miles per passenger. Transport costs are usually measured in relation to mass of fuel (kg/pkm), or by fuel volume (L/pkm), and sometimes, particularly when different types of fuels or energy sources are compared, in energy units (MJ/pkm, MJ/tkm). It is necessary to distinguish between available transport capacity (seats, pkm, or tkm) and real load (e.g. seats actually occupied); the latter is called the revenue passenger kilometre (RPK), and its ratio to the available pkm is the passenger load factor (PLF). Be warned that the many different units still in use in this engineering field, contribute in a relevant way to the difficulty in mastering the subject, and to the abundant errors in calculations).

Human mobility has had two big jumps in range and spread: in the 15th century with the onset of oceanic voyages that for the first time covered the globe and transported quantities of people and goods between continents, and in the 20th century with the widespread use of personal cars and the first travels to extra-terrestrial space.

We intend to focus on vehicle propulsion, so that the first splitting may be on the propulsion system itself, and the rest of the vehicle (named vehicle for short). The propulsion system may be split in three parts (Fig. 1): an energy source (e.g. the fuel tank), a device converting the energy source to mechanical energy (the engine), and the end actuator exerting the thrust force (call it a thruster for short, but it may be the wheels of a car, the crew propeller...).

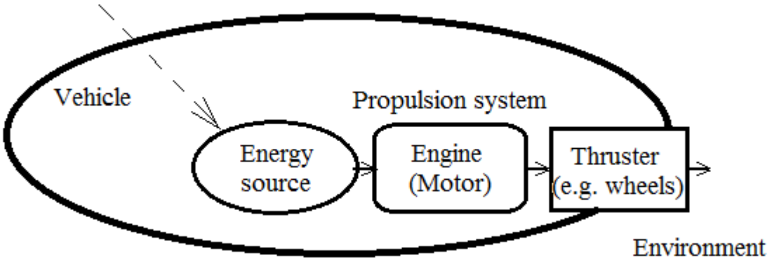

Fig. 1. The vehicle (e.g. a car) contains the propulsion system which consists of an energy source (e.g. fuel tank, or electric battery), an engine (e.g. internal combustion engine, or electric motor), and the force actuator on the environment (drawn half-way outside the system on purpose, since it must directly act on the environment). The broken arrow stands for the possibility of energy coming from an outside source (e.g. electrical contacts, solar radiation).

Vehicle propulsion is required to accomplish several tasks: to sustain horizontal constant speed against air and road drag on the surface of a planet, to climb (i.e. to gain potential energy in a force field), to accelerate, to change attitude (i.e. change angular momentum instead of linear momentum)...

## FUNDAMENTALS

Propulsion of a system (on purpose changing its motion relative to an environment) requires the existence a second system and action upon it, as explained by the evolution laws for an isolated system:

- First law of Mechanics (Newton's 1st law, first proposed by Galileo): all relative motions would tend to continue, if there were no force applied on it (neither drag, nor thrust, and no gravitation). It is instructive comparing this statement with a similar one from Aristotle: all relative motions tend to decay, if there is no thrust.
- Second law of Mechanics (Newton's 2nd law) for an isolated system: $\Delta(m\vec{v})=\Delta(\Sigma m_i\vec{v}_i)=0$, i.e. the linear momentum of an isolated body (the sum of the linear momentum of all its parts) cannot be changed. Notice that an inertial reference system for speeds is implied. The same applies to angular momentum: $\Delta(I\vec{\omega})=0$, which is a consequence of the conservation of the linear momentum of all its parts. For an isolated body to change its motion, external forces are needed (propulsion), $\mathrm{d}(m\vec{v})/\mathrm{d}t=\sum F_i$, and since globally $\mathrm{d}(m\vec{v})/\mathrm{d}t=0$, any force must be balanced by an opposite one (action-reaction law, or Newton's 3rd law); i.e. to propel something, **something else must be pushed to the rear**. Propulsion demands a second system (the one to throw back), which can be either carried on with the vehicle (before ejecting it), or can be a separate external

system (like a rope, or a road, or a fluid, to grasp on), or a combination of a fuel carried on and an oxidiser taken from the environment, like in a car. Newton's 2nd law teaches that motion is best quantified by momentum, $m\vec{v}$, instead of speed, $\vec{v}$.

- First law of Thermodynamics for an isolated system: $\Delta E=\Sigma\Delta E_i=0$, i.e. the energy of an isolated body (sum of the energy of its parts) cannot be changed, if some subsystems gains, others must lose. For the two systems implied in propulsion, vehicle and environment, as the second system gets energy for the first one, the vehicle must be losing energy (while being propelled), or a third system to borrow energy from, must be available (e.g. energy from the Sun). In conclusions, to propel, energy is required; i.e. being propelled (and keeping alive, in general) requires a support system (the larger the better: the environment).
- Second law of Thermodynamics for an isolated system: $\Delta S=\Sigma\Delta S_i\geq 0$, i.e. entropy, the variable measuring the distribution of conservative properties within a system (energy, mass, and momentum), tends to increase with time (i.e. conservative properties tend to get dispersed, randomly in absence of force fields, while conserving their total amounts), so that all relative motion tends to decay, and propulsion is an artificial fight against motion decay, at the expense of some energy-source expenditure; i.e. propulsion dissipates energy.

The creation of relative motion (between a vehicle and its environment), the maintenance of relative motion (against the omnipresent dissipative effects), and the controlled destruction of relative motion (different to natural decay), demands some propulsion system able to apply a force to the vehicle, $\vec{F}$ named thrust or traction (sometimes symbolised by $T$, but $F$ is more common and leaves $T$ for temperature), always balanced with an opposite force on the environment according to the 3rd Newton's law. The change in momentum in an inertial reference frame is called impulse, $\vec{J}\equiv\Delta(m\vec{v})=\int\vec{F}\mathrm{d}t$. According to the chosen system:

-for the combination vehicle+environment: $\vec{F}_{veh}+\vec{F}_{env}=\mathrm{d}\left(m_{veh}\vec{v}_{veh}+m_{env}\vec{v}_{env}\right)/\mathrm{d}t=0$.

-for either the vehicle or the environment:

$$\vec{F}=\frac{\mathrm{d}(m\vec{v})}{\mathrm{d}t} \tag{1}$$

In summary, we see that propulsion requires a force (thrust) to cause motion (advance), what implies a second system being pushed backwards (the environment, some propellant, or both) and an energy source (internal or external to the moving body, e.g. fuels, or solar power). Without a second system to be pushed backwards, propulsion is not possible despite how much energy is available; and, without energy expenditure, propulsion is not possible either.

Propulsion science is based on Mechanics, Thermodynamics, and Hydro/Aerodynamics (and related matters on material sciences, electronics, control theory, and so on). We do not intend here to give an overview of all those scientific and technological fundamentals of propulsion; e.g. little mention is given to the mechanics of reciprocating engines or turbomachinery (i.e. the machines that transfer energy between a rotor and a fluid, including both turbines and compressors), nothing about lubrication problems, control systems, etc.

## ENERGY NEEDED FOR PROPULSION

Propulsion requires an energy source able to do some mechanical work: thrust times relative displacement. The thrust is needed to push the body forwards (or, what is the same, to push the environment backwards), but there is no propulsion without the advance motion. Only in the undesirable limit of very slow motion and under the unattainable limit of full energy recovery, the energy needed to move between equipotential locations would tend to zero. The energy used for propulsion finally dissipates (usually in a turbulent wake behind the vehicle, but sometimes with surface-friction contribution, and always with some heat transfer outwards to balance internal dissipation). Friction occurs in linear motion (e.g. between piston and cylinder), and circular motion (e.g. wheel-axle and bearings), or in any other geometry with relative motion (wheel rolling, pulleys and gear transmissions, and so on).

Transport is a major world's energy consumer (about 30 % of primary energy, only second to industry, and larger than residential and commercial consumption), burning most of the world's petroleum, and significantly contributing to air pollution. Propulsion is usually the main energy consumer in a vehicle, but energy is also needed for other purposes on board: space conditioning (heating and refrigeration), radio-communications, lighting duties, entertainment (if manned), payload operations (including life support systems, if any)...

The energy balance for the isolated system composed of a vehicle (moving body in general) and the environment (including ejected propellants), can be split into the kinetic term and all the others (chemical, potential, thermal...), $\Delta E+\Delta E_{\mathrm{env}}=0=\frac{1}{2}mv^2+\frac{1}{2}m_{\mathrm{env}}v_{\mathrm{env}}^2+\Delta E_{\mathrm{others}}+\Delta E_{\mathrm{others,env}}$. The minimum energy to propel from rest a vehicle of mass $m$ at speed $v$ (absolute values for velocity, i.e. with $mv=m_{\mathrm{env}}v_{\mathrm{env}}$ from Newton's second law), is:

$$\Delta E_{\min}=\frac{1}{2}mv^2+\frac{1}{2}m_{\mathrm{env}}v_{\mathrm{env}}^2=\frac{1}{2}mv^2\left(1+\frac{v_{\mathrm{env}}}{v}\right) \tag{2}$$

hence, the best approach to get a given momentum for the vehicle, $m_{veh}\vec{v}_{veh}$, is to make use of a large environmental mass $m_{\mathrm{env}}$ (e.g. the Earth) to minimise $v_{\mathrm{env}}$; however, for ‘moving without touching ground’ (e.g. in water, air, or space), the contrary is the common, i.e. a small mass (environmental mass or on-board-carried mass) is forced to move backwards at high speed (propeller and jet propulsion).

The energy needed for propulsion may come from an external source (i.e. from the environment, e.g. solar radiation), or from a dedicated external link (e.g. powered rail, tracking laser beam), or from a storage on board (e.g. elastic clockwork, batteries, propellants), although the most common on ground is to carry a chemical fuel aboard and make it react with the oxidiser in the environment. Therefore, two propulsion subsystems are usually involved, besides the energy source: an engine that transforms the energy source (e.g. chemical, solar) into mechanical energy (e.g. to a shaft), and a thruster (or propeller) that transforms the mechanical energy to propulsion energy (in pure jet engines, one may consider the nozzle as the end actuator). Accordingly, two efficiencies can be defined: $\eta_{\mathrm{engine}}$ and $\eta_{\mathrm{propeller}}$ (see Propulsion efficiency, below). By the way, a logistic problem arises with fuel-based propulsion: fuel stations should be available at the destination point (and usually along the path), or the vehicle would have to carry aboard the return fuel too, with the penalty it imposes on payload.

The propulsion power for sustained horizontal uniform motion is $\dot{W}_p = Fv_0$, where $F$ is the thrust applied to balance drag $D$ ($F$=$D$ in sustained horizontal uniform motion), and $v_0$ the vehicle speed relative to ground or to a quiescent fluid environment. To this respect, mind that all speeds are relative to a given frame, and that kinetic energy depends on the chosen frame. We have used above a frame fixed to the initial motionless state ($m_{veh}\vec{v}_{veh} + m_{env}\vec{v}_{env} = \text{const}$, $\tfrac{1}{2}m_{veh}\vec{v}_{veh}^2 + \tfrac{1}{2}m_{env}\vec{v}_{env}^2 + \Delta U$ =constant, where $\Delta U$ stands for the internal energy store, e.g. in a propellant). For a frame moving with the vehicle, $\vec{v}_{veh} = 0$, inertial forces have to be added in no-uniform motion, and forces applied to the vehicle produce no work, so that, for an energy balance where propulsive work appears explicit, a fix reference frame is preferred over a moving one.

Different types of propulsion systems are to be considered below, but total operating time, $\Delta t_{\text{op}}$, poses some limitations on the energy source that should be kept in mind from the beginning:

- For short operational life, say $\Delta t_{\text{op}}$<1 day, initial installation cost should be minimised, and electrochemical batteries (with electric motors) may be the best solution for low total energy needs, say <10 MJ (the power supplied may be large for very short times). For much larger energy needs, however, chemical gasdynamic systems (e.g. rockets) may be needed. On Earth applications, part or all of the propulsion system may be recovered, greatly decreasing the expense.
- For long operational life, say $\Delta t_{\text{op}}$>1 day, a reusable engine with a large fuel tank, or with a renewable energy source, is required, if total energy needs are not too low (some watch/clock batteries last several years). The typical propulsion system is the internal combustion engine (ICE, reciprocating or gas turbine) with a fuel tank, used in all kinds of vehicles except spacecraft, where photovoltaic solar power is the rule. Some other technologies have special applications (e.g. in space), and might take a larger share of general applications in the future, as solar powered systems (photovoltaic or thermal), fuel cell systems (the fuel cell is a kind of battery with the chemical reactives in external tanks), or nuclear power (already used in deep space probes).

Related to operating times, most introductory analysis of propulsion systems assume the engine is operating under steady conditions, but, mechanical inertia must be taken into account during engine acceleration and deceleration. On the contrary, for the fluid flowing through the engine, transitory effects can always be neglected because the residence time of the fluid inside the engine is of order $10^{-2}$ s, much shorter than the time the engine takes to accelerate, or the characteristic time of environmental changes.

Concerning energy usage in propulsion, and later on its effect on the environment, one may split the source-to-sink energy transformations in three stages:

- From raw source to the fuel tank, i.e. from crude-oil extraction at the well, to refineries, fuel stations, and vehicle fuel-tank, or from renewable energy collectors (e.g. wind farms, or on-board photovoltaic panels) to battery storage.

- From fuel tank to wheels (to thruster, in general, e.g. a propeller, or a nozzle). This is the main interest here, i.e. the efficiency of the propulsion system (engine plus propeller), or the related parameter 'specific fuel consumption, SFC, and not only at cruise conditions but at part loads (intermediate energy storage may significantly contribute to overall efficiency at changing power demands).
- From thruster to the environment, including total propulsive power required (mainly dependant on vehicle drag and mass), and emissions in general: chemical (e.g. toxic, acidifying, ozone-layer depleting, global warming), thermal (e.g. hot jets), mechanical (e.g. noise)...

The propulsion system contributes with its mass and volume to the power demanded by the vehicle as a whole, and is the main source of emissions, but major improvements can be achieved by optimising the vehicle (e.g. less heavy, more streamlined, better thermal insulation and solar-gain control, etc.

To these direct energy use in vehicle propulsion, one should add the contribution (to energy use and to environmental impact) of the associated infrastructures (installation and maintenance).

### Types of energy sources. Specific energy storage

The energy source in a propulsion system is usually carried on board, with the consequent decrease in available payload mass and volume, the two exceptions being the capture of electromagnetic radiation (e.g. solar vehicle, linear electric motor), and the sliding electric contacts (e.g. the catenary).

- Combustion of chemical fuels, fossil or renewable, using ambient air as oxidiser or not. This is the most widespread form of powering in propulsion. If we relax the 'combustion' constrain, and include other fuel processing means as electrochemical (batteries and fuel cells) and biochemical (animal muscles), it is clear that fuel energy is the rule. For the fuel cell on Earth, it is customary to store only the fuel (pure hydrogen in most cases) and use the surrounding oxygen in the air as oxidiser; presently, these gases must be feed pressurised to the fuel cell to better use these expensive components (similarly to supercharging in internal combustion engines, ICE); the compression may take 20 % of the power produced.
- Electrical energy, usually stored in electrochemical batteries (kind of non-flowing fuels; much higher capacity can be obtained storing the fuels apart with an electrolyser, to be later used in a fuel cell), and rarely stored in supercapacitors. However, most of the times, electricity for propulsion is being generated on spot by thermal engines (e.g. for electric trains).
- Solar energy (electromagnetic radiation), captured by photovoltaic panels, or by solar thermal collectors (heating the working fluid) in thermal engines.
- Wind energy, using sails or kites (not only on the sea, but on land or ice too).
- Nuclear energy, from fission reactors (e.g. nuclear submarines), or from radioactive decay (e.g. RTG).
- Mechanical energy stored in elastic springs, or compressed air, or flywheels. The only prototype vehicles built were based on compressed-air tanks, but they had very low specific energy and thus short endurance, and the heat loses in filling the tank and in supplying compressed air to the engine, was a handicap; however, their use as energy storage in hybrid propulsion (see below) can be advantageously used.

- Human power: pedalling, rowing, or pushing/pulling a vehicle. Human power (in the order of $10^2$ W) and animal power (in the order of $10^3$ W) is ordinarily too small and expensive (a saying when mechanical propulsion developed was: 'steam horses don't eat when not working').

Specific energy (energy density) of different energy sources is presented aside. Sometimes the word 'fuel' is used to refer to the energy source in general (e.g. when 'refuelling' is used for recharging the batteries of an electric car).

## FORCE NEEDED FOR PROPULSION

To change relative motion we need an external force (Newton's 1st law) which may be in the direction of motion (retarding or advancing the linear motion), or in any other direction (bending the trajectory). Really, all forces exist in pairs (Newton's 3rd law): if a second system exerts a force $\vec{F}_{21}$ on a first one, then the first one exerts a force $\vec{F}_{12}$ on a second one, such that $\vec{F}_{21}+\vec{F}_{12}=0$. We may think on this active force on the vehicle, or in the reactive force on the second system, but thinking on the vehicle moving, while we observe it from the second system, i.e. a fix reference frame, best illustrates the work done by these forces, and changes in kinetic and potential energies (and, though it is the same saying 'the vehicle advances' than 'the environment moves back', the former best focuses our attention).

Let start assuming an inertial reference frame, and account only for surface forces, i.e. electromagnetic forces of contact (e.g. our finger pushing an object along a table top). Besides some volumetric forces of electrical origin (electromagnetic, in general) which will be considered in due time, we are not considering gravitational forces (volumetric) as providing thrust, i.e. we do not call propulsion to the mere free fall, including unpowered orbital flight, or the uniform motion relative to an arbitrary inertial reference frame.

Thrust is the pressure or shear force on the vehicle exerted by the propulsion system. Notice that sometimes subtle differences are ascribed to thrust (viewed as a reactive force) and traction (viewed as an active force), and we say, for instance, that we walk because we produce traction on the ground with our feet, and not because we produce thrust, but consider a pedal-boat and a pedal-tricycle and guess if you are pushing or pulling, or consider a bicycle and guess if the pedalling person is producing thrust or traction (in fact, there are special pedals where you can do work either by pushing or by pulling the pedal).

Thrust is then a pressure or shear force on the propulsion system (as with our fingertip) exerted by the environment as a reaction of it being pushed back, and, a

According to the environment in contact with the moving object, we may consider different kinds of propulsions:

- On the surface of a solid environment, propulsion is usually by solid friction forces (but it might be by rockets or any other means). Consider a normal car at rest; the force that makes it advance (thrust, $F$) is due to road friction with the wheels, i.e. $F=\mu W_{car}$, where $W_{car}$ is the weight of the car, and $\mu$ the friction coefficient. Over a perfectly slipping surface ($\mu$=0) the car will not advance whatever the engine power and wheel spin rate. A pressing force is also needed. Of course, the road/wheel friction (that must provide the thrust) is not enough to make the car go; an engine is needed to provide the power involved in propulsion, $\dot{W}_{\mathrm{shaft}}$, which is the torque imposed on the wheels (equal to the friction torque) $Q=FR=\mu W_{\mathrm{car}}R$, times the wheel's angular speed, $\omega=2\pi N$, i.e. $\dot{W}_{\mathrm{shaft}}=Q\omega=\left(\mu W_{\mathrm{car}}R\right)\left(2\pi N\right)=\mu W_{\mathrm{car}}v$, where $R$ is the wheel radius, $N$ the rotation rate in rps (though often stated in revolutions per minute, rpm), and $v$ the advance speed of the car. It is clear that a pressing force (against the solid surface) is needed; in this case the vehicle weight (inertial forces as in roller-coaster looping); we see that the weight of the car increases the required propulsion power (and fuel consumption) not only for acceleration but at constant speed.

- On a fluid media, without contact with a solid surface, propulsion must be by fluid pressure and shear forces on the surface of the propulsion system, i.e. on paddles, propeller blades, compressor blades, and/or on the walls of the combustion chamber (or equivalent propellant chamber). In most cases the environmental fluid provides the thrust when the propulsion system forces it to flow backwards; e.g. if a mass-flow-rate of air, $\dot{m}_{\mathrm{a}}$, is accelerated from an entrance speed $v_0$ to an exit speed of $v_{\mathrm{e}}$ (in a vehicle reference frame), the thrust is $F=\dot{m}_{\mathrm{a}}\left(v_{\mathrm{e}}-v_0\right)$.
- On vacuum, without contact with a solid surface, propulsion requires throwing some system-mass backwards, i.e. thrust is created by pressure and shear forces (of the fluid being expelled) on the walls of the combustion chamber (or equivalent propellant chamber); e.g. if a mass-flow-rate of propellants, $\dot{m}_{\mathrm{p}}$, is accelerated from rest (on a vehicle reference frame) to an exit speed of $v_{\mathrm{e}}$, the thrust is $F=\dot{m}_{\mathrm{p}}v_{\mathrm{e}}+p_{\mathrm{e}}A_{\mathrm{e}}$, ($F\approx\dot{m}_{\mathrm{p}}v_{\mathrm{e}}$ leaving aside the small effect of exit pressure).

Now we go in more detail with different types of propulsion systems focusing on the end actuator (the part providing thrust) more than on the type of energy source or the engine used to transform it to mechanical energy of propulsion.

## Types of thrusters

The thruster is the device producing the force of thrust. We have seen that they must push something back (to propel the vehicle forward), and we can distinguish between pushing back a solid (when advancing along the surface of that solid), and pushing back a fluid (from the environment or from inside the vehicle).

To put vehicular propulsion in a wider perspective, we add here some special thrusters not included in traditional propulsion systems:

- Projectiles, i.e. bodies launched, but no longer propelled. They follow a ballistic trajectory (from Gr. βάλλειν, to throw). The projectile is accelerated (propelled) for only a very short time; motive power is usually mechanic, or fluiddynamic, but it may be electric or magnetic. Some projectiles stay connected by a cable to the launch equipment after launching (wired projectiles).
  - Hitting, i.e. when an object changes relative speed because of a chock with another solid; e.g. a football kick. This is an almost instantaneous push.
  - Throwing (by hand, bow or catapult), i.e. a kind of progressive hit received from a solid; e.g. a basketball shooting.

  - Blowing, i.e. acceleration of an object by a fluid being externally forced to flow in the advance direction. This may comprise the open blow by wind (or a fan, or our mouth), and the ducted blow, ranging from our blowing through a tube, to shooting.
  - Shooting, i.e. a violent blowing of a bullet by compressed air or the gases generated in a chemical reaction. Maximum bullet speed occurs at the muzzle of the gun (limited to 1.5 km/s in practice), but maximum pressure inside the barrel takes place at a third of the run or so. The kinetic energy of the bullet is around a third of the lower heating value of propellant charge.
  - Pyrotechnics, i.e. the explosion of a small amount of pyrotechnic material like in a bullet, but aiming at slowly moving away a large mass (instead of giving a high speed to a small mass as in shooting). Pyrotechnic devices are used in most rockets (explosive bolts) to separate different parts (and as igniters), in military aircraft for seat ejection, etc.
- Cable vehicles, i.e. non-autonomous vehicles (without own propulsion plant), relying on cables or other mechanical transmission to be pushed/pulled.
  - Surface cable cars, where the cable (or chain) only provides the push/pull, with part of vehicle weight being supported either on ground (usually on rails, e.g. funiculars), or on the water surface (cable ferries).
  - Suspended cable cars, where vehicles hang from the cables (e.g. téléphériques, aerial lift, ski lift).
  - Elevators (lifts), rail-guided cable-cabins moving vertically.
- Propelled vehicles, i.e. craft with their own propulsion plant, usually with its own energy source (e.g. fuel tank or battery), but sometimes with a distant energy source (solar radiation, electrical catenary...).
  - Solid traction, i.e. when the reactive force is applied on a solid environment in contact with the vehicle, either by a 'hard' mechanism (gears), or 'soft' mechanism (friction), with the engine in the vehicle. The contact is usually forced by the gravity force (vehicle weight). The engineering standard for traction on solids is the friction wheel used in cars and trains, but it is worth realising that the standard in terrestrial animal locomotion is walking on two or four legs, with minimum or intermittent contact like in running and jumping (the reason is that wheels need smooth roads, uncommon in nature). Humans have used animal traction since the Neolithic period. In boat punting, the punter propels the boat on shallow waters by pushing against the water bed with a pole. On the contrary, marine and aerial animals, as well as marine, aerial, and space vehicles (and some land vehicles) rely on fluiddynamic forces for propulsion.
  - Sailing (old Ger. *sek*-, a cut), i.e. a vehicle propelled directly by wind energy acting on a sail (a large cut of fabric supported by a mast), usually over water and in the direction of motion, but possible over land and ice too. It seems to have existed in Mesopotamia around 4000 BCE, and being used in ancient Egypt since 3200 BCE to move upstream the Nile river by taking advantage of prevailing North winds (moving downstream was just by water entrainment). Sailing windward is more complex, requiring a coordination of air forces on the sail with water forces on the keel and rudder, and stacking (i.e. following a zigzag course).

- Rowing, and, in general, marine propulsion by solids partially immersed on water, which may be: by oars (a long wooden shaft with a flat blade at the end, grabbed at the other end, and with the fulcrum fixed to the vessel at the tholes); by paddles (similar to oars but not connected to the boat, sometimes with one blade in each end, like in kayaks); or by paddle wheels (a number of wide paddles set around the periphery of a spoke wheel at the stern or one side of a boat, like in the Mississippi paddle steamers). An oarsman can yield up to 500 W during several minutes of exhausting effort, achieving a boat speed of up to 5 m/s, slightly growing with the number of oarsmen (up to 200 oarsmen were used in the largest galleys and triremes). Boats can be propelled with just one oar at or near the stern, like in a gondola. Aquatic animal locomotion can be included here, from the simplest propulsive systems composed of cilia and flagella, to the swimming of arthropods and vertebrates, including humans.
- Flapping, and, in general, aerial or marine propulsion by fully immersed non-rotating surfaces (flying or swimming). Besides propulsion (thrust to advance), the flapping motion in air must provide lift, whereas, under water, weight is balance hydrostatically, and propulsion is based mainly on the caudal fin (flapping from side to side in fish, or up and down in cetaceous), with other fins used for manoeuvre and stability (e.g. the dorsal fin is used to stabilize the animal against rolling and to assist in sudden turns). Powered aerial locomotion (squirrels and other forest animals can only glide) has always being by flapping wings, contrary to aircraft that only work on propellers or in jet engines (insects developed flight 350 million years ago, then pterosaurs evolved from reptiles some 200 million years ago (and disappeared 70 million years ago; some had 10 m wingspan), then birds evolved from bipedal reptiles about 150 million year ago, and finally bats evolved from gliding mammals some 60 million years ago. This has made flying very hard for humans to understand, as it involved varying flapping and advancing speeds, and different wing shapes.
- Gliding (old Ger. *glidan*-, to slip), where a vehicle is propelled by a natural cross-flow in the fluid environment. Sailplane gliders take advantage of naturally occurring currents of rising air in the atmosphere (thermals) to soar and remain airborne (i.e. to have lift and to overcome drag). Underwater gliders, however, propel themselves by forcing small changes in their buoyancy, creating up and down motions which are converted to horizontal motions by normal wings; although most underwater gliders are powered by a battery that moves a diaphragm to change buoyancy at surface and bottom positions, they might be propelled by taking advantage of the ocean thermal gradient; they only need a few watts to slowly propel themselves forward (at <0.5 m/s), sequentially diving and surfacing, all around the oceans. Surfing is a kind of gliding at a wavy water surface; the surfer rides on the forward face of a moving wave which is usually carrying the surfer towards the shore.
- Propellers, i.e. blades radially disposed, usually unducted like in the typical axial fan used for ventilation, but sometimes shortly ducted. Propellers are further analysed aside.
- Nozzles, i.e. the end of a tube where the exit jet forms (sometimes, the mouth-piece of a vacuum cleaner aspirating air is named nozzle too). As in fans, there are stationary

nozzles not used for propulsion but to inject fluids at high speed (like in diesel injectors, supersonic wind tunnels, hose nozzles, nozzle flow-meters...), and propulsion nozzles, either by means of a gas jet, or by means of a liquid jet like in water-jet marine propulsion. Gas nozzles are further analysed aside.

Propulsion by mere gravitational forces (free fall, planetary slingshot) has not been considered here; propulsion based on extra-terrestrial solar wind (solar sails), and space plasma (electrodynamic tethers), have not been considered either.

## ENERGY CONVERSION DEVICES

A propulsion system needs a devise to transform the energy source (e.g. a fuel) into mechanical energy (to make it run): the engine. Besides this main energy conversion device, some others may be present, like mechanical, hydraulic, or electric transmission systems.

We have seen that propulsion systems can be classified according to the energy source (e.g. chemical propulsion, electrical propulsion...), according to the type of engine (e.g. internal combustion, electric...), according to the end actuator (e.g. wheeled, screw-propelled, jet-propelled), according to the application (e.g. road and rail systems, marine systems, or aerospace systems), but it is clear that the engine is the key element in engineering studies. The standard propulsion systems are:

- On land, the reciprocating internal combustion engine (ICE).
- On water, the ICE-driven screw propeller, used in small boats, large ships, and submersibles.
- On air, the turbofan and turboprop.
- In space, the rocket, where the reactive force is due to the expelling of part of the vehicle mass (the propellant).

The above classification is for convenience; e.g. the water and air propulsion systems might be considered jointly since both hydrodynamic and aerodynamic propulsion work on the same principle: take some ambient fluid and push it backwards.

### Types of practical engines

An engine or motor is a machine designed to convert some energy source into useful mechanical motion (rotation or translation). Most practical engines used in propulsion (on land, water, air and space) are directly or indirectly driven by the combustion of a fuel with an oxidiser (most of the times oxygen from the surrounding air, or liquid oxygen carried on board). The largest share of the electricity that drives electric motors is generated by combustion too. Combustion creates contaminants and hazards.

Since 1900, the internal combustion engine (ICE), is by far the most used in propulsion. During the 19th century, however, the steam engine (an external combustion machine), was preponderant in marine, railway, and road (unpaved) propulsion. Before 1800, only animal power or wind was used in propulsion.

In chronological order of their widespread use in propulsion, practical engines may be grouped as:

- Steam engines were the first type of mechanical heat engines, giving rise to the Industrial Revolution in both, manufacturing and transportation. The main handicap as a propulsion system was its low fuel efficiency: in oceanic routes, steam boats had to use sails when coal was exhausted, and railways needed frequent coal (and water) depots along the way. Another handicap appeared when competing with ICE, steam power plants are heavier and bulkier, but for about a century (19th), the steam engine had no rival for ships (at sea and along inland canals), for railways, and for roads, although road vehicles were horse-driven in its majority; some highways were paved, and most had turnpikes to pay for use. In 1900, about half of the road cars were still steam-powered; the steam car was safer and easier to drive (no need of clutch and transmission, ease of power reverse for braking), had a quieter and smoother run (no explosions), and could be fuelled with anything that burned (a big problem for ICE engines during WWI). But in the 1920s Ford Model T petrol car was mass produced at a price that fell from 1000 $/unit to 260 $/unit in the decade), with a dry mass of 540 kg, and a 15 kW engine (a 4-cylinder in-line with 2.9 L of total displacement, able to run not only on gasoline, but on ethanol and kerosene too), propelling to a maximum speed of 20 m/s (72 km/h) with a consumption of about 15 L every 100 km. About 1920, steam-car production was practically abandoned: a steam car was almost an order of magnitude more expensive than a Ford T (and five times its weight). Steam engines are still used in nuclear vessels (using nuclear fission instead of external combustion), and in traditional LNG carriers (to take advantage of the boil-off gas).
- Reciprocating internal combustion engines, either spark ignited (SI-ICE, usually gasoline fuelled), or compression ignited (CI-ICE, usually diesel fuelled); fuel properties can be found aside. They are the standard engines in road and marine propulsion in all power ranges, in non-electrified railroad, and in the smallest aircraft and airships. Modern ICE developments (electronic direct injection and three-way catalytic converter in gasoline engines, and the common-rail direct injection with exhaust particle filter in diesel engines) have greatly reduced their contaminant emissions and improve their performances. There seems to be a tendency towards ICE developments combining characteristics of conventional gasoline engine and diesel engines, like in homogeneous charge compression ignition (HCCI). Modern diesel engines may reach maximum efficiencies of $\eta$=0.4 in cars (and almost 0.5 in large ships), but this halves in the normal part-load usage (SI-ICE have about 10 % lower efficiency than CI-ICE).
- Electrical motors, where electromagnetic forces make a rotor to spin. As the end-mover (i.e. acting directly on the wheels or propellers), the electric motor is the standard in railway propulsion, has taken a share in marine propulsion, and is being introduced into the car market, first in hybrid configuration (an ICE for high-power demand and battery charging an electric motor for city traffic), and possibly by using fuel cells. Advanced (non-rotating) electromagnetic motors are briefly considered here under Space propulsion, but there are ground applications too, like the Maglev train.
- Jet engines, the standard in aircraft propulsion, either as turbofans for large airliners, or as turboprops and turboshafts (not really 'jet' engines, but jointly considered because of similarity), used in medium-size aircraft (both, small fixed-wing aircraft, and rotorcraft). Jet engines usually refer to air-breathing gas engines though rockets are jet engines too; marine water-jet propulsion, based on ducted propellers or centrifugal pumps, are driven by diesel engines. Jet engines are not

used in road, railway, and marine propulsion because of their low performance in specific fuel consumption, especially at part loads. Gas turbines are used in some fast ships.

- Rocket engines, the standard in missiles and spacecraft propulsion. Notice that this is the only propulsion system that cannot run only on batteries or nuclear power; rockets must lose some mass (air-breathing jet engines not necessarily; they might be solar-powered). The ejection of momentum can be achieved by pressure-release of a fluid (inert, like when releasing an inflated balloon open-mouth, or reactive, like in fireworks), or by electromagnetic acceleration of a plasma. Really it is not mass but momentum that must be ejected, but a photon rocket is still a dream. There are some animals that used a kind of rocket propulsion, but only for a very short time because the loss of mass would be prohibitive otherwise (e.g. cephalopods use jet propulsion by taking in water and squirting it back out in a burst). Rocket engines are under international traffic arms regulations (ITAR).
- Other engine types like the rotary Wankel engines (used in some unmanned vehicles), Stirling engines (used in some submarine air-independent propulsion systems), compressed-air engines, free-piston engines, and so on, are only testimonial in propulsion applications.

Engines can also be classified by application. Leaving aside non-moving engines (e.g. those driving electrical appliances, air-compressors, pumps, electrical generators...), engines for propulsion can be grouped as:

- Road engines (or automotive engines), for cars, motorcycles, or heavy vehicles (buses trucks, and rolling machinery, even if for non-road use). Small rolling machinery engines like lawn movers may be included here too. ICE engines dominate, basically running on gasoline or diesel, with a minority using natural gas (18 million), or GLP (17 million), or bioethanol (6 million). Electric engines are taking a share in the small power range (about 7.5 million as of Dec-2013).
- Marine engines. ICE engines dominate, with a few gas turbine applications on fast ships, and steam turbine applications nowadays only used in nuclear vessels and in liquefied-natural-gas tankers.
- Railway engines. Electric motors fed from catenary grids dominate in developed regions, with diesel engines on the rest.
- Aircraft engines. Turbofans and turboprops dominate the market, with ICE being used in the smallest aircraft.
- Space engines. Rocket engines are the only possibility in space, but the use of air-breathing engines in the first stage of launchers might appear in the future.
- Others: model engines (for crawling, rolling, boating, or flying), robot actuators, lawn movers. Small ICE and electric motors are used.

Usually there is just one main engine in a vehicle (or two; four at the most, in the largest aircraft and ships), but, in some instances, there is a tendency towards distributed propulsion, where the traditional high-power engines are replaced by multiple low-power and smaller engines.

In the past, besides safe operation, the main objective on heat engine design was to get better fuel efficiency, particularly on propulsion applications (were fuel storage competes with payload); nowadays, a new question has entered the scene: new design must meet ever-stringent environmental regulations.

We focus here on engines for propulsion, but there are more items in a vehicle than the engine (a lot of people view the vehicle engine as a troublesome need, and dream of electric cars as the 'engineless' future). By the way, among the engine-related characteristics of a vehicle, the refuelling period and duration outstand.

## Heat engine thermodynamics

The thermodynamics of heat engines is presented aside, covering: gas power cycles, vapour power cycles, combined power cycles, and cogeneration of power, heating, and cooling.

It is worth to recall some basic ideas on heat engines:

- Most heat engines are not 'pure heat engines' but thermochemical combustion engines operating in an 'open cycle' mode, i.e. fuel and oxidiser are input, subjected to a few thermodynamic processes, and discarded. The pioneering steam engine was closer to a pure heat engine (it may run on any heat source, like solar power or nuclear power; the same for the Stirling engine).
- The four basic thermodynamic processes applied to the working fluid in a heat engine are: compression, heating, expansion, and heat removal; the latter is most often performed at the exhaust to the environment and not inside the engine, but it is essential to understand engine efficiency.
- Most heat engines must be started by means of another motor (usually an electric motor and batteries, later to be recharged by the heat engine and electrical generator, but think of a car with exhausted batteries!).
- Engines are rated on their maximum deliverable power (design point), but most engines work a lot of time at partial load (off-design operation).
- There is always ambiguity between possibility and actuality, in engineering and aside. This is recognised, for instance, when we say explicitly 'deliverable power' and 'delivered power' instead of simply 'engine power', but it is not so clear in many other engine-related parameters; e.g. when we say that a compressor has a pressure ratio of 30 ($p_2/p_1=30$), we often forget that it depends on what is downstream (the compressor alone in open air would have $p_2/p_1=1$ no matter how fast is made to rotate). Keep in mind that language cannot be too precise because cost (in words, time, or money) escalates with precision, so that be prepared to understand different uses of 'power' and 'energy', adiabatic heating in combustion chambers, etc.

## Engine parameters: testing-variables, design-variables, and functions

The main performance parameter of an engine is its maximum deliverable power, e.g. $\dot{W}_{\text{shaft}}$; in the case of propulsion, motive power is thrust times advancing speed, $\dot{W}_{\text{prop}}=Fv_0$, and thrust $F$ becomes an equivalent size-defining engine variable (or torque in shaft engines). From the many parameters characterising an engine, there are a few that can easily be changed during operation; others require some specialised tuning, and most others are fixed by design.

Testing. For an existing engine, once it is running, only two variables can be changed during test:

- Fuel input, usually controlled by the driver or pilot as a fuel-lever-command position.
- Environmental conditions, which, for a given design, and in accordance with the fuel lever, control air intake. Most modern reciprocating engines work supercharged instead of naturally aspirated, i.e. admitting compressed air to the cylinders, usually with a centrifugal compressor coupled to a centrifugal turbine driven by the exhaust gases (turbo); that is particularly important in aero-engines because of air-density decreasing with altitude (altitude fixes temperature and pressure in the ISA model).

Design. It depends on engine type, and can be grouped as:

- Size, both in power and geometrical units (they are related):
    - Engine maximum deliverable power (or maximum thrust, or maximum torque). Engine size in propulsion applications may range from large units delivering tens of megawatts in the largest ships and aircraft, to minute engines delivering tens of watts in model craft (there are research projects on micro aerial vehicles, like Delfly from TU-Delft, with a mass of 3 g, of which 1 g for the 20 mAh Li-polymer battery and 0.5 g for the electric motor, flapping wings at 30 Hz, with a 3 min endurance).
    - Active volumetric size, e.g. total displacement volume, $V_d$, in reciprocating engines, entry or exit area in turbines, fan diameter....
- Thermodynamic parameters:
    - Maximum temperature ($T_{max}$), or maximum wall temperature ($T_{max,wall}$). This sets a limit to possible materials used in engine walls and moving parts.
    - Maximum pressure, or effective pressure, or pressure related variables. In jet engines, maximum pressure ($p_{t3}$, ahead of the combustion chamber), or overall pressure ratio (OPR=$\pi_{03}\equiv p_{t3}/p_{t0}$) are used. In displacement engines (reciprocating or rotatory), the compression ratio $r=V_2/V_1$ is used (instead of the pressure ratio $\pi=p_2/p_1$ used in gas turbines); besides, a much used variable is the mean effective pressure (MEP, or $p_{ME}$), defined as output work per unit of piston engine displacement, $p_{ME}\equiv W_{cycle}/(\pi D^2L/4)=\dot{W}_{shaft}n_T/(NV_d)=2\pi Q n_T/V_d$, where $W_{cycle}$ is the work per power stroke, $D$ and $L$ piston bore and stroke, $\dot{W}_{shaft}$ is shaft power, $n_T$ the number of crank-turns in a power cycle ($n_T$=1 in two-stroke engines, $n_T$=2 in 4-stroke engines), $N$ is the crank speed in revolutions per second, $V_d$ engine displacement (number of cylinders time $\pi D^2L/4$), and $Q$ shaft torque ($\dot{W}_{shaft}=\omega Q=2\pi NQ$). Naturally-aspirated engines typically have maximum MEP (i.e. at maximum torque) of $p_{ME}$=0.9..1 MPa if spark-ignited, or $p_{ME}$=0.7..0.9 if compression-ignited; turbocharged engines may have $p_{ME}$=1.1..1.7 for gasoline, and $p_{ME}$=1.4..1.9 for diesel. Notice that, for a given power and displacement, a 4-stroke engine needs double MEP than a 2-stroke one, i.e. the latter can be lighter, so important for aero-engines (no wander why most of the model ICEs are of 2-stroke type (either glowplug or diesel).
- Other parameters (geometrical, material, thermal, electric...); e.g. overall dimensions, weight, bypass ratio in a turbofan, fan pressure ratio....

For given design and operating data, physical equations (mass, energy, momentum, and entropy considerations) yield the performances as:

- Absolute values (depending on engine size): power, thrust, torque engine mass, fuel consumption, air flow-rate, exit speed...
- Relative variables (quotient of two absolute magnitudes):
    - Installation: power/engine_mass, thrust/engine_mass (or better thrust/weight)...
    - Operational: power/fuel_consumption, thrust/fuel_consumption... Often, the inverse is given (e.g. range for a unit fuel volume).
    - Internal: air-to-fuel ratio ( $A \equiv \dot{m}_{\mathrm{a}}/\dot{m}_{\mathrm{f}}$ ), engine temperature ratio (ETR), engine pressure ratio EPR, nozzle pressure ratio (NPR)...

A design point is first established (usually the maximum power (or thrust, or torque) point at standard sea-level conditions, and afterwards the off-design analysis is carried out, changing the environmental conditions (e.g. altitude and flight speed), and fuel throttling.

## HYBRID PROPULSION

In many occasions, a single engine, or a single fuel on the same engine, cannot offer good performances in all phases of propulsion (e.g. booster thrust for acceleration or climbing, sustained thrust on cruise, idle or descent operation, subsonic and supersonic flight, and so on). A hybrid propulsion system uses two or more distinct power sources to move the vehicle (e.g. a fuel tank and an electric battery), with different engines, and usually separate power trains to drive the end actuator (wheel, propeller...).

Hybrid propulsion is often restricted to two-engine-type systems, with hybrid-fuel systems covered under Dual-fuel engines: Otto-type ICE able to operate either on gasoline, or on LPG, or on compressed natural gas; Diesel-type ICE able to operate either on diesel or on liquefied natural gas, usually with two different fuels at a time (diesel and natural gas, or diesel and gasoline). When the different fuels are premixed and stored on the same fuel tank, then the term 'flexible fuel engine' seems more appropriate (e.g. different gasoline/alcohol mixtures, diesel/biodiesel, and so on).

In general, according to power transmission, hybrid propulsion systems may operate:

- In parallel, when both engines work at a time, each adding power to the final propelling device; e.g. the wheels in a car, the skew propeller in boats and aircraft.
- In series, when only one engine at a time drives the final propelling device; the two engines may be working at a time, but only one drives, the other is feeding the latter, directly or through an energy storage device (e.g. an ICE moves an electrical generator that feeds an electric motor).

### Type of hybrid vehicles

Most hybrid vehicles use a main thermal engine (ICE) and a smaller electric motor, and the main handicap is on the powerful batteries needed to operate with the ICE off. Although Pb-acid and Ni-MH batteries are the most mature (lead-acid ones being the cheapest, by far), the tendency is to implement Li-ion batteries, much more expensive (500 €/kWh in 2013). The range on battery power is meagre for a car: about 4 km/kWh, Li-ion batteries are more efficient and with very high specific energy: 0.6 MJ/kg (0.17

kWh/kg), in comparison with 0.15 MJ/kg (0.04 kWh/kg) for lead-acid batteries. And battery recharging is a slow process; at present, battery swapping seems too exposed to fraud and hidden damage, if not by the same owner. Notice that even pure electric vehicles (PEV, or just EV) contribute to $CO_2$ (and other) emissions because of the present large fuel share in electricity production (in 2010, electric cars contributed some 100 g/km of $CO_2$, in comparison with 200 g/km for a gasoline car).

Another type of hybrid engine stores energy as compressed air instead of electrical batteries, and in that way the reciprocating engine may recover kinetic energy on braking and descents (the control of cylinder valves becomes complicated, to change from internal-combustion to air-compressor mode).

According to vehicle type, one may consider the following hybrid-vehicle types:

- Two-wheeled hybrids, where the basic human pedalling is supplemented (e.g. to assist uphill) either by a small ICE (with its fuel tank), or by a small electric motor (with its battery). Electric bikes (ebykes) are light vehicles (<40 kg), with a small motor (<200 W, < 1 kW peak), a battery pack (<1 kWh, typically 10 Ah at 48 V, with a mass about 6 kg), and an electrical controller that automatically cuts power to the motor when the speed is higher than 25..30 km/h (or when the brakes are applied). The battery charger is usually off-board (it may take 2..6 h to recharge).
- Hybrid cars (usually named HEV, hybrid electric vehicles), where the traditional ICE (gasoline or diesel) is supplemented with an electric motor and a more powerful battery or a separate battery pack. Although the first HEV was already built in 1899, hybrid designs were abandoned until the 1990s, when massive production started (by beginning of 2014 there were almost 8 million HEV worldwide). Two kind of HEV can be distinguished:
    - Short-range HEV, say less than 5 km (at less than 50 km/h). They use a small electric motor (say <30 kW) and a larger battery than pure ICE cars, which is automatically recharged by the ICE engine when needed (not rechargeable from the grid). This is the most developed kind HEV. The typical example (e.g. Toyota Prius), has a $V_d$=1.6..2 L displacement gasoline engine of 70..100 kW, and a 25..30 kW electric motor. The ICE works on a modern Atkinson cycle; i.e. an Otto cycle with highly-retarded closure of the intake valve (some fresh-air charge is rejected, lowering the compression ratio to about $r$=8, but leaving a larger expansion ratio, about $r$=12); instead of pushing some fresh-air back into the intake manifold, in other designs this fresh-air is directed to the exhaust manifold (opening the exhaust valve instead of leaving open the intake valve), with the advantage of some valves and walls cooling; the engine must be of direct-injection type. These Atkinson cycles yield better fuel efficiency (38%) than comparable Otto engines (<35 %), but have smaller specific engine power (less MEP), and consequently lower torque (not a problem at low speeds because the companion electric motor provides a large torque).
    - Long-range HEV (better known as plug-in hybrid vehicle, PHV), say more than 30 km (at about 80 km/h). They use a larger electric motor (say >50 kW) and a high-voltage Li-ion battery pack of 8..10 kWh (100..150 kg of mass, usually located under the rear seats), which is recharged from the grid (with a few hours of recharging time). There are more expensive and less developed. If the car battery where smartly connected to the grid at

home, the batteries might be used for home-electricity backup and peak loads, with the associated saving.

- Hybrid buses and trucks. Hybrid heavy vehicles (including mobile industrial machinery) usually have a large diesel engine driving an electric generator (or a hydraulic pump, alternatively), an electric wire power transmission (or hydraulic piping), and one or more electric motors (or hydraulic motors). Essentially, they are diesel-electric transmissions and not hybrid vehicles because there is only one source of power (they do not have a battery pack for propulsion). In spite of the double power-conversion loses (e.g. mechanical to electrical at the ICE, and electrical to mechanical at the wheels or propellers), there are advantages in distributing power through wires or pipes rather than mechanical elements (especially when there are multiple drives and long transmission lines). Major hybrid developments are taking place in city buses, where environmental issues have higher priorities.
- Hybrid trains. A hybrid train is a locomotive using electric motors at the driving wheels, and a diesel engine. Electricity to the wheel-motors may come from the diesel engine (and generator), or transmitted through a catenary. Intermediate battery storage may be incorporated, in which case the catenary may not be needed for short travels, and dynamic breaking can be used advantageously.
- Hybrid ships. Most are diesel-electric, like in non-nuclear submarines, which were the earliest hybrid-propulsion vehicles after the transition of sailing ships to motor ships (ships with both mast-mounted sails and steam engines were built from 1803 to 1884).
- Hybrid aircraft. A demonstration airplane has been built by Boeing adding a PEM fuel cell (with its own $H_2$ fuel tank to power a conventional motor glider). Aircraft operations on ground are being powered by electric motors at the wheels, fed from the auxiliary power unit (APU). The DA36 E-Star aircraft (first flown in 2013) employs a series hybrid powertrain with the propeller being turned only by a Siemens 70 kW electric motor, with an on-board 30 kW Wankel rotary engine and generator. The classical turbojet has a maximum Mach number of $M$=3; all high-supersonic and hypersonic aircraft foreseen must use hybrid propulsion systems (e.g. a turbojet and a ramjet), sometimes named combined-cycle jet engines.
- Hybrid rockets make use of two propellants in two different states of matter: one solid (usually the fuel), and the other either gas or liquid (the oxidiser, usually). There are some applications where rocket engines are combined with air-breathing engines, like in some present missiles and future single-stage-to-orbit (SSTO) crafts.

Combined thermodynamic-cycle power plants (e.g. a gas turbine with a bottom steam turbine) are rarely used in propulsion, and other combinations like the turbo-compressor (turbocharger) used in reciprocating engines are not considered hybrid systems because the turbo shaft is uncoupled to the propulsion shaft (but a modified gas-turbine system might be developed in which the combustion chamber is not steady but with a reciprocating piston generating additional power). The turbocharger was first developed for aircraft piston engines in the 1920s, to compensate the air-density decrease with altitude), being nowadays common in road and marine engines, often with an intercooler heat-exchanger before entrance to the piston engine, to further increase volumetric efficiency.

## THRUST AND ADVANCE SPEED

Propulsion implies relative motion against natural forces. Thrust, $F$ (sometimes the symbol $T$ is used for thrust, but we keep $T$ for temperature), is the force pushing a body to move against natural forces, e.g. to sustain horizontal constant speed of a vehicle against air and road drag (or water drag), or accelerating it, or climb up (i.e. moving against a force field, but not the natural fall by gravity forces, neither the orbiting flight).

Thrust and traction have the same motion effect on the body (but in the pushing the body get compressed, and in the pulling stretched). Thrust is usually understood to be in the direction of motion, although the term is often used more generally, and thrust may have other components to provide some lift, or stirring control (e.g. gimballed thrust is the system of thrust vectoring used in most modern rockets, including Saturn V and the Space Shuttle).

For best propulsion efficiency (less fuel needed), thrust must be aligned with advancing velocity, even for orbital changes in space propulsion. However, there are some important cases where thrust must contribute to lift, like in helicopters and in vertical take-off and landing (VTOL) aircraft. This is achieved by vertical-axis propellers (permanently like in helicopters, or able to tilt from horizontal axis to vertical axis in some aircraft), or by deflecting down the exhaust jet of the main engines (or better by jet deflection and an additional shaft-driven ducted fan located behind the cockpit).

If Newton's second law (1) is applied to a fixed mass $m$ but considered as a continuum (an integral of differential masses $\mathrm{d}m=\rho \mathrm{d}V$, where $\rho$ is local density), it becomes:

$$\vec{F}=\frac{\mathrm{d}(m\vec{v})}{\mathrm{d}t}=\int_V \rho\frac{\mathrm{D}\vec{v}}{\mathrm{D}t}\mathrm{d}V=\int_V \frac{\partial(\rho\vec{v})}{\partial t}\mathrm{d}V+\int_A \vec{v}\rho\vec{v}\cdot\vec{n}\mathrm{d}A \xrightarrow[\text{(x-component)}]{\text{steady}} F_x=\int_A v_x\rho\vec{v}\cdot\vec{n}\mathrm{d}A \qquad (3)$$

with velocities referred to an inertial reference frame (if velocities are relative to the vehicle body, $\vec{v}_\mathrm{r}$, and the vehicle is moving with arbitrary body-velocity $\vec{v}_\mathrm{b}$ relative to the inertial coordinate system, then $\vec{v}=\vec{v}_\mathrm{r}+\vec{v}_\mathrm{b}$ should be substituted in (3), given way to acceleration terms (linear, angular, centripetal and Coriolis) which can also be accounted for as inertial forces (nil in the steady motion of a body).

On jet engines, thrust is the force exerted on inner parts by the fluid flowing through the engine, whereas drag is the force exerted on outer engine. However, the latter is usually considered globally with the rest of aircraft surface drag. With velocities relative to the engine;

- Thrust in a rocket is:

$$F_\mathrm{rocket}=\dot{m}_\mathrm{p}v_\mathrm{e}+\left(p_\mathrm{e}-p_0\right)A_\mathrm{e}\approx\dot{m}_\mathrm{p}v_\mathrm{e} \qquad (4)$$

which may be interpreted as 'nozzle flow thrust', $\dot{m}_\mathrm{p}v_\mathrm{e}$ (where $\dot{m}_\mathrm{p}$ is the propellant mass flow rate, and $v_\mathrm{e}$ its exit speed relative to the nozzle), plus a 'pressure thrust', $(p_\mathrm{e}-p_0)A_\mathrm{e}$ (if pressure at the exit section is not the same than that of the environment), the latter being much smaller than the former.

- In a simple turbojet (no longer used; it corresponds to the core stream in a turbofan), the thrust is (also known as net thrust when a gross thrust is defined for $v_0$=0 in (5); i.e. $F_{\text{net}} = F_{\text{gross}} - \dot{m}_a v_0$):

$$F_{\text{turbojet}} = \left(\dot{m}_{\text{a}} + \dot{m}_{\text{f}}\right) v_{\text{e}} - \dot{m}_{\text{a}} v_0 + \left(p_{\text{e}} - p_0\right) A_{\text{e}} \approx \dot{m}_{\text{a}} \left(v_{\text{e}} - v_0\right) \tag{5}$$

  which may be interpreted as 'nozzle flow thrust', $\left(\dot{m}_{\text{a}} + \dot{m}_{\text{f}}\right) v_{\text{e}}$, minus 'intake flow thrust', $\dot{m}_{\text{a}} v_0$, plus 'pressure thrust', ($p_e$–$p_0$)$A_e$. Here, $\dot{m}_{\text{a}}$ and $\dot{m}_{\text{f}}$ are the air and fuel mass flow rates (the later almost two orders of magnitude smaller), and $v_e$ and $v_0$ the exit and flying speed relative to the engine. As for rockets, the pressure term can be neglected to a first approximation.

- In a turbofan (i.e. a double-flow turbojet) total thrust is the sum of the two streams (the core flow to be burned, and the fan flow, just compressed and expanded):

$$\begin{aligned} F_{\text{turbofan}} &= \left[\left(\dot{m}_{\text{a,core}} + \dot{m}_{\text{f}}\right)\left(v_{\text{e,core}} - v_0\right) + \left(p_{\text{e,core}} - p_0\right) A_{\text{e,core}}\right] + \left[\dot{m}_{\text{a,fan}}\left(v_{\text{e,fan}} - v_0\right) + \left(p_{\text{e,fan}} - p_0\right) A_{\text{e,fan}}\right] \\ &\approx \dot{m}_{\text{a,core}}\left(v_{\text{e,core}} - v_0\right) + \dot{m}_{\text{a,fan}}\left(v_{\text{e,fan}} - v_0\right) \end{aligned} \tag{6}$$

  In this case, the pressure terms are really zero because the two stream exit subsonically, and the approximation is just by neglecting the added fuel.

- In a propeller of diameter $D$ (swept area $A=\pi D^2/4$), thrust may be thought of as a pressure jump across the disc, $\Delta p$, such that $F=A\Delta p$, or as a velocity jump, $\Delta v$, such that $F=A\rho(v_0+\Delta v/2)\Delta v$, but it is difficult to find the so-defined parameters $\Delta p$ and $\Delta v$ in terms of detailed design (number and shape of blades, pitch, rotation rate, etc. Perhaps the simplest estimation of thrust is based on the shaft power supplied by the engine, $\dot{W}_{\text{shaft}}$, and a typical advancing speed, $v_0$, assuming a propeller efficiency of about $\eta_p$=0.8, since, from definition of $\eta_p$ (see Propellers, aside):

$$F = \frac{\eta_{\text{p}} \dot{W}_{\text{shaft}}}{v_0} \tag{7}$$

  but mind that $\eta_p \to 0$ when $v_0 \to 0$.

Besides thrust, propulsion requires relative motion, usually advancing at a certain speed, $v_0$ (relative to the environment), in the direction of thrust. Thrust may be applied not in the direction of motion, to help in manoeuvres or to directly compensate weight in hovering, even without relative motion, with the same engine providing propulsion and lift).

Notice that the benefit of propulsion is vehicle displacement (travelling), and the cost is the energy spent on this displacement, thrust being but an intermediate requirement. That is why we measure a vehicle-engine efficiency in amount of fuel to run a certain distance, and that is why the overall propulsion efficiency is defined as the propulsive power, $Fv_0$ (thrust power), divided by the raw power taken from the energy source (see Efficiency, below).

Engines must be capable not only of maintaining a regular nominal motion, but to accelerate the vehicle from standstill, and decelerate it, climb and descend. Acceleration and climbing usually demand the largest power (particularly when combined, as in aviation).

According to engine type, thrust may take the following forms:

- Wheel-friction propulsion (as in road and railway applications), with wheel radius $R$, rotating with angular speed $\omega$, and advancing at speed $v_0=\omega R$ when not sliding. Thrust (advancing force) is obtained by applying a torque, $Q=FR$ (force time radial distance) to the wheels with the axis perpendicular to the advancing speed; the torque (adding all driving wheels) is usually larger than the engine torque (because of different rotation rates), but the power, $\dot{W}_{\text{shaft}}=Q\omega$, is the same (except for the minor friction losses in the gear-box and bearings).
- Propeller propulsion (as in ship and aircraft applications), with diameter $D$, rotating with angular speed $\omega$ (or at $n=\omega/(2\pi)$ revolutions per second, rps) and advancing at speed $v_0$ through a fluid medium. Thrust is obtained by applying a torque to the propeller, as in wheel friction, but here with the axis aligned with the advance speed); thrust and torque can be set as $F=c_F\rho\omega^2D^4$ and $Q=c_Q\rho\omega^2D^5=\dot{W}_{\text{shaft}}/\omega$, where the thrust coefficient $c_F$ and torque coefficient $c_Q$ (and the related power coefficient, $\dot{W}_{\text{eng}}=c_P\rho\omega^3D^5$) are functions of the propeller advance ratio, $J\equiv v_0/(\pi nD)$, and blade pitch angle, $\theta$, if controllable; see Propellers, aside).
- Jet propulsion (as in spacecraft, aircraft, and some high-speed marine applications), with jet diameter $D$, exit speed $v_\text{e}$, and, for air-breathing and water jets, an incoming speed $v_\text{i}$ (usually approximated as the advance speed $v_0$); recall that all speeds are relative to the engine. According to type of fluid used in the jet, one may distinguish:
    - Air-breathing jets, where a jet engine accelerates an air mass-flow-rate $\dot{m}_\text{a}$ from the incoming air speed $v_0$ to an exit speed $v_\text{e}>v_0$ (both relative to the engine body), having neglected, as usual, the contribution of added fuel mass-flow-rate since $\dot{m}_\text{f}/\dot{m}_\text{a}=1/A<<1$. Thrust is $F=\dot{m}_\text{a}\left(v_\text{e}-v_0\right)$, where a possible exit-pressure term is neglected, and entry speed is approximated by flying speed $v_0$. The smallest jet engine (the AT-180 turbojet developed for radio-controlled aircraft) produces 90 N, whereas the largest jet-engine (the turbofan GE90-115B fitted on the Boeing 777-300ER), has a thrust of 570 kN. For jet engines with double flow (turbofan), total thrust is $F=\dot{m}_{\text{a,core}}\left(v_{\text{e,core}}-v_0\right)+\dot{m}_{\text{a,fan}}\left(v_{\text{e,fan}}-v_0\right)$. The ratio thrust-to-weight was $F/W_{\text{eng}}=4$ in the first turbojets (1940), and it was $F/W_{\text{eng}}=10$ in 2010.
    - Water jets, where a diesel engine or a gas turbine engine accelerates a water mass-flow-rate $\dot{m}_w$ from the entrance speed to an exit speed $v_\text{e}$. Thrust is $F=\dot{m}_w\left(v_e-v_0\right)$. Although commercial water jet propulsion is only used in high-speed boats, some toys used water jets in an air environment (of course, this water rockets last very short times).
    - Autonomous jets (rockets), with propellant mass-flow-rate $\dot{m}_\text{p}$ (often gaseous, but it may be a liquid, or a plasma), issuing at speed $v_\text{e}$ (relative to the rocket, unrelated to the its advancing speed, $v_0$). Thrust is $F=\dot{m}_\text{p}v_\text{e}+A_\text{e}\left(p_\text{e}-p_0\right)\approx\dot{m}_\text{p}v_\text{e}$, where the exit-pressure term may be positive or negative but relatively small (often neglected). Notice the importance of exhaust speed in rockets: thrust is proportional to $v_\text{e}^2$ ($F=\dot{m}_\text{p}v_\text{e}=\rho_\text{e}v_\text{e}^2A_\text{e}$).

> An example of small-thrust chemical rocket may be the eight 1 N hydrazine thrusters on each of the Galileo navigation satellites, or the 24 cold-gas units mounted in the astronaut backpack in ISS, producing 3.6 N each, but ion thrusters are much smaller. The largest rocket was Saturn V with 34 MN (the STS had 30 MN in total: two SBR with 12.5 MN each, plus three cryogenic SME of 1.8 MN each). Some rocket-types have special names: a thruster is a small propulsive device used by spacecraft and watercraft for station keeping, attitude control, in the reaction control system, or long-duration, low-thrust acceleration; a vernier rocket is a smaller thruster used for fine attitude control (after the mathematician Pierre Vernier, inventor of the calliper in 1631).

As a summary of thrust equations we may take approximately:

$$\left.\begin{array}{l} F_{\text{propeller}}=c_F\rho n^2D^4 \quad (\text{with typical } c_F{=}c_{F_0}\cdot\cos\dfrac{v_0}{nD} \text{ and } c_{F_0}\approx 0.1 \text{ and } v_0<nD) \\ F_{\text{turbofan}}=\dot{m}_{\text{a,core}}\left(v_{\text{e,core}}-v_0\right)+\dot{m}_{\text{a,fan}}\left(v_{\text{e,fan}}-v_0\right) \\ F_{\text{turbojet}}=\dot{m}_{\text{a}}\left(v_{\text{e}}-v_0\right) \\ F_{\text{rocket}}=\dot{m}_{\text{p}}v_{\text{e}} \end{array}\right\} \qquad (8)$$

where $\rho$ is the density of the medium, $n$ is propeller rotation rate [rps] ($D$ is diameter), $v_0$ is vehicle speed (incoming air speed), and subindices a, f, 0, e, and p stand for air, fuel, incoming, exit, and propellant, respectively. Notice that the exit-pressure effect can be neglected in a first approximation (it is exactly null for subsonic exit, and for adapted supersonic nozzles), as well as the fuel flow rate against air flow rate (in air-breathing engines).

### Propulsion efficiency

For steady horizontal motion at speed $v_0$ (relative to ground or to a still fluid medium), the energy dissipated just by the motion is $Dv_0=Fv_0$ (where $D$ is the drag force to overcome and $F$ the thrust applied; $F=D$ for uniform horizontal motion). The overall propulsion efficiency can be defined by comparing this propulsion energy with the raw energy source (e.g. energy in the fuel, solar energy). This overall propulsion efficiency, $\eta_{\text{tp}}$, is often split in two parts: the energy efficiency from raw source (usually thermochemical) to a mechanical form of energy, $\eta_{\text{t}}$ (which depends on the engine type), and the energy efficiency of the conversion of that mechanical energy to the propulsion energy, $\eta_{\text{p}}$. Both values depend on the type of engine. Restricting the analysis to internal combustion engines, we may group them in:

- Shaft engines.
- Jet engines (non-rocket, i.e. air-breathing jet engine).
- Rocket engines.

Shaft propulsion. When a shaft-engine applies a shaft power $\dot{W}_{\text{shaft}}=Q\omega$ ($Q$ is the torque and $\omega$ the angular speed) to a propeller (let us think of a blade-propeller as used in boats and small aircraft, but the same applies to solid-friction propellers like the wheels in a car), the propulsion efficiency, $\eta_{\text{p}}$, engine efficiency, $\eta_{\text{e}}$ (often named $\eta_{\text{t}}$ for heat engines, i.e. thermal-to-mechanical energy conversion engines), and overall efficiency, $\eta_{\text{tp}}=\eta_{\text{t}}\eta_{\text{p}}$, are defined as:

$$\eta_p \equiv \frac{Fv_0}{\dot{W}_{\text{shaft}}},\quad \eta_t \equiv \frac{\dot{W}_{\text{shaft}}}{\Delta\dot{E}_{\text{source}}} = \frac{\dot{W}_{\text{shaft}}}{\dot{m}_f h_{\text{LHV}}},\quad \eta_{tp} \equiv \eta_t\eta_p = \frac{Fv_0}{\Delta\dot{E}_{\text{source}}} = \frac{Fv_0}{\dot{m}_f h_{\text{LHV}}} \tag{9}$$

where a chemical energy source has been assumed in the final development, with a fuel flow-rate of $\dot{m}_f$ and a lower heating value of $h_{\text{LHV}}$ in the combustion of the fuel used (e.g. $h_{\text{LHV}}$=43 MJ/kg for diesel and kerosene fuels); mind that sometimes, instead of the lower heating value symbol here used, $h_{\text{LHV}}$, the symbol $h_p$ 'heating power', or even $L$, are used.

Propulsion efficiency $\eta_p$ (i.e. of the propeller itself) is zero at rest, and varies with advancing speed to a maximum value of about $\eta_p$=0.9, as later shown in Fig. 2.

Thermochemical efficiency $\eta_t$ (i.e. of the engine itself) is zero when idling (the fuel is used just to overcome the internal friction to keep the engine running), and grows to about $\eta_t$=0.4 (0.5 in the largest marine engines).

The $\dot{m}_f/\dot{W}_{\text{eng}}$ term appearing in (9), is the power-specific fuel consumption (or unitary-power fuel consumption, more commonly named brake specific fuel consumption, BSFC, or simply SFC, with the symbol $c_{sp}$ often used), and is often used as an alternative to engine efficiency to compare different engines, both for propulsion and non-propulsion applications, but the effect of different fuels may distort the comparison since $\dot{m}_f/\dot{W}_{\text{eng}} = 1/(\eta_t h_{\text{LHV}})$. BSFC is usually given in grams of fuel per kilowatthour; e.g. a modern turboprop may have a figure of $c_{sp}$=300 g/kWh, a modern gasoline car 250 g/kWh, a modern diesel car 200 g/kWh, and the most efficient reciprocating engine (a large two-stroke marine diesel) 170 g/kWh; e.g. for the latter, 170 g/kWh=170/3600 (g/s)/kW=0.047 (kg/s)/MW=0.047 kg/MJ, which yields $\eta_t$=1/( $h_{\text{LHV}}$ $\dot{m}_f/\dot{W}_{\text{eng}}$ )=1/(43·0.047)=0.50.

The $\dot{m}_f/F$ term appearing in (9), is the unitary-thrust fuel consumption (or thrust-specific fuel consumption, TSFC) is not much used in shaft propulsion but commonly used in jet engines; care must be paid since the same the same short-name (SFC) and the same symbol ($c_{sp}$) are used in both cases.The fact that BSFC is commonly used in shaft propulsion, instead of TSCF, is that engine and propeller are clearly separate items, and the BSFC may apply not only to propulsion but to other uses of the engine, whereas simple jet engines are only used for propulsion.

Air-breathing jet propulsion

For steady horizontal motion at speed $v_0$ of a vehicle propelled by a simple jet engine (i.e. a turbojet, not a turbofan), the momentum balance in the direction of motion, reduces to:

$$F = \dot{m}_a(v_e - v_i) + \dot{m}_f v_e + \left[(p_e - p_0)A_e - (p_i - p_0)A_i\right] \approx \dot{m}_a(v_e - v_0) \tag{10}$$

where $F$ is thrust (net thrust). The approximation at the right end of (10) considers the intake speed equal to the flight speed ($v_i$=$v_0$), neglects the contribution of fuel mass in momentum (it is typically $\dot{m}_f/\dot{m}_a$

=1/$A$=0.02), and neglects the effect of pressure imbalance between entry and exit (it is zero in subsonic exhaust, and in supersonic exhaust with adapted nozzle, and small in not-adapted supersonic nozzles).

The propulsion efficiency is defined as thrust power $Fv_0$ divided by the mechanical power developed, which, in a ground-reference frame (in the frame moving with the vehicle the thrust makes no work) is $Fv_0 + \frac{1}{2}\dot{m}_a(v_e - v_0)^2$, i.e. the propulsive power to match the environment drag, plus the kinetic energy of the exhaust jet relative to ground. Namely:

$$\eta_p = \frac{Fv_0}{Fv_0 + \frac{1}{2}\dot{m}_a(v_e - v_0)^2} \overset{p_e=p_0}{=} \frac{\dot{m}_a(v_e - v_0)v_0}{\dot{m}_a(v_e - v_0)v_0 + \frac{1}{2}\dot{m}_a(v_e - v_0)^2} = \frac{2}{1 + \frac{v_e}{v_0}} \tag{11}$$

where the same approximation as above has been introduced. As always, the propulsion efficiency $\eta_p$ is zero at zero speed (there is thrust but not propulsion), and grows to 1 as the exit speed decreases towards the flight speed (but then the thrust approaches zero). Notice that the same thrust, $\dot{m}\Delta v$, may be obtained with a large $\Delta v$ and small flow rate or vice versa, but the propulsion efficiency, $\eta_p$=2/(2+$\Delta v/v$), shows that it is better to have a small $\Delta v$ and a large $\dot{m}$, what has been implemented in practice by high-bypass turbofans (where only a tenth of the overall air-flow-rate goes through the thermal engine, i.e. the core, and the larger part is simply forced backwards mechanically with the fan, much like in a conventional propeller).

Jet engines are heat engines, following a Brayton cycle like terrestrial gas turbines, but the mechanical energy they produce is not extracted in a shaft, but is conveyed by the gas flow as increment of kinetic energy. In a reference frame moving with the aircraft, this kinetic energy increment is $\frac{1}{2}\dot{m}_a v_e^2 - \frac{1}{2}\dot{m}_a v_0^2$, but in a reference frame fixed to the ground, the one that should be used to combine with the propulsive efficiency defined in (11), this kinetic energy increment is $\frac{1}{2}\dot{m}_a(v_e - v_0)^2 - 0$ (which added to the thrust power, $Fv_0$, becomes the same, and thus the turbojet engine efficiency (or thermal, or thermochemical) is:

$$\eta_t \equiv \frac{Fv_0 + \frac{1}{2}\dot{m}_a(v_e - v_0)^2}{\frac{1}{2}\dot{m}_f v_0^2 + \Delta\dot{E}_{\text{source}}} \approx \frac{\dot{m}_a(v_e - v_0)v_0 + \frac{1}{2}\dot{m}_a(v_e - v_0)^2}{\dot{m}_f h_{\text{LHV}}} = \frac{\frac{1}{2}\dot{m}_a(v_e^2 - v_0^2)}{\dot{m}_f h_{\text{LHV}}} \tag{12}$$

where the $\frac{1}{2}\dot{m}_f v_0^2$ term in the denominator corresponds to the initial kinetic energy of the fuel in the fix reference frame, but it is always negligible ($\frac{1}{2}\dot{m}_f v_0^2 << \Delta\dot{E}_{\text{source}}$). Thence, its overall propulsion efficiency (or thermo-propulsive efficiency) is:

$$\eta_{tp} \equiv \eta_t\eta_p = \frac{Fv_0}{\Delta\dot{E}_{\text{source}}} = \frac{v_0}{\frac{\dot{m}_f}{F}h_{\text{LHV}}} = \frac{v_0}{c_{sp}h_{\text{LHV}}} \tag{13}$$

where $c_{sp}\equiv\dot{m}_f/F$ is the thrust specific fuel consumption (TSFC or SFC). The best turbofans in the 2010s have cruise values in the range $\eta_t$=0.50..0.55, and $\eta_p$=0.75..0.80 ($\eta_{tp}$=0.40..0.44), with practical limits estimated as $\eta_t$=0.60 and $\eta_p$=0.95 ($\eta_{tp}$=0.57). SFC is often used as an alternative to overall propulsion efficiency to compare different engines, but the effect of vehicle speed $v_0$ may distort the comparison (e.g.

fuel consumption in a present large airliner is typically $\dot{m}_\mathrm{f}/F$=16 (g/s)/kN, whereas Concorde had 34 (g/s)/kN, but, as the later travelled at double the speed of the former, their overall efficiencies are nearly the same). For an airliner at cruise ($v_0$=250 m/s), burning kerosene ($h_\mathrm{LHV}$=43 MJ/kg), with $\dot{m}_\mathrm{f}/F$=16 (g/s)/kN, the overall efficiency (12) is $\eta_\mathrm{tp}=250/(16\cdot10^{-6}\cdot43\cdot10^{6})=0.36$; in a modern airliner at cruise, about 40 % of the fuel energy goes to propulsion ($Fv_0$), another 40 % goes as thermal energy of engine exhausts, and the 20 % rest goes as excess kinetic energy (not only the horizontal component at engine exhaust, $\frac{1}{2}\dot{m}_\mathrm{a}\left(v_\mathrm{e}-v_0\right)^2$, but the vertical component developed by the wing to provide the momentum that balances aircraft weight).

Rocket propulsion

Rocket propulsion requires energy (internal or external), an exhaust of a fluid (carried within), and the engine to combine energy and mass-flow-rate. In a cold-gas rocket, exergy is in the pressure difference, the gas is on store, and the engine is simply a pressure-gas-reservoir with a nozzle and controls. In a chemical rocket (solid or liquid), exergy is in the chemical bonding, the gas is generated on the fly by fuel/oxidiser combustion, and the engine is as simple as before (reservoir and nozzle) except for the very high temperatures. In an electrical rocket, exergy is from solar cells or nuclear disintegration, the gas is stored within, and the engine is a complicated electromagnetic system.

For steady horizontal motion at speed $v_0$ of a vehicle propelled by an autonomous jet engine (a rocket), the momentum balance in the direction of motion, reduces to:

$$F=\dot{m}_\mathrm{p}v_\mathrm{e}+(p_\mathrm{e}-p_0)A_\mathrm{e}\approx\dot{m}_\mathrm{p}v_\mathrm{e} \tag{14}$$

where $\dot{m}_\mathrm{p}$ is the mass-flow-rate of propellants exhausted (fuel and oxidiser), and the pressure term (positive or negative, but relatively small) may be neglected to a first approximation. Notice that exit is always supersonic (to minimise spent propellant), and the nozzle is said 'adapted' if gas pressure at the exit stage, $p_\mathrm{e}$, coincides with environmental pressure, $p_0$; but exit pressure may be $p_\mathrm{e}>p_0$ (e.g. under vacuum), or $p_\mathrm{e}<p_0$ (e.g. at sea level). The propulsion efficiency, $\eta_\mathrm{p}$, is defined (as always) as the ratio of thrust power, $Fv_0$, to the mechanical power developed, which, in a ground-reference frame (recall that in the frame moving with the vehicle the thrust makes no work) is $Fv_0+\frac{1}{2}\dot{m}_\mathrm{p}\left(v_\mathrm{e}-v_0\right)^2$, i.e. the propulsive power to match the environment drag, plus the kinetic energy of the exhaust jet relative to ground. Namely:

$$\eta_\mathrm{p}=\frac{Fv_0}{Fv_0+\frac{1}{2}\dot{m}_\mathrm{p}(v_\mathrm{e}-v_0)^2}\overset{p_\mathrm{e}=p_0}{=}\frac{\dot{m}_\mathrm{p}v_\mathrm{e}v_0}{\dot{m}_\mathrm{p}v_\mathrm{e}v_0+\frac{1}{2}\dot{m}_\mathrm{p}(v_\mathrm{e}-v_0)^2}=\frac{2}{\frac{v_\mathrm{e}}{v_0}+\frac{v_0}{v_\mathrm{e}}} \tag{15}$$

As always, the propulsion efficiency is zero at $v_0$=0 (there is thrust but not propulsion), and grows to 1 as the exit speed decreases towards the flight speed (but contrary to turbojets, the thrust does not approach zero at $v_\mathrm{e}=v_0$, and the advancing speed of the rocket may be larger than the exit flow speed, as typical in orbital rockets). Efficiencies (15) and (11) are plotted in Fig. 2.

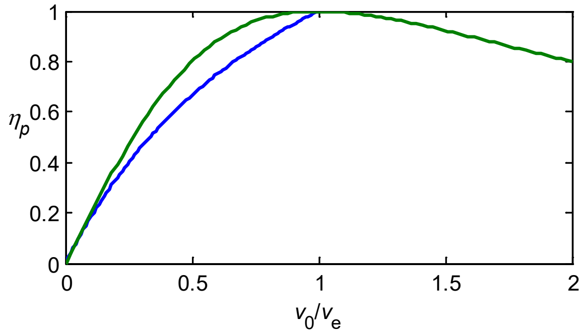

Fig. 2. Propulsion efficiency, $\eta_\mathrm{p}$, vs. flight speed to exit speed ratio, $v_0/v_\mathrm{e}$, for a rocket (green line) and an air-breathing engine (blue line).

Most rockets are heat engines that transform the heating power of a fuel/oxidiser mixture (of lower heating value $h_\mathrm{LHV}$), into mechanical energy (the kinetic energy of the jet in a fixed reference frame, $\tfrac{1}{2}\dot{m}_\mathrm{p}\left(v_\mathrm{e}-v_0\right)^2$); but there are other rocket types not based on chemical reactions (e.g. cold gas thrusters and ion thrusters). Leaving that aside, the rocket engine efficiency and its overall propulsion efficiency are:

$$\eta_t \equiv \frac{Fv_0+\tfrac{1}{2}\dot{m}_\mathrm{p}\left(v_\mathrm{e}-v_0\right)^2}{\tfrac{1}{2}\dot{m}_\mathrm{p}v_0^2+\Delta\dot{E}_\mathrm{source}} \approx \frac{\dot{m}_\mathrm{p}v_\mathrm{e}v_0+\tfrac{1}{2}\dot{m}_\mathrm{p}\left(v_\mathrm{e}-v_0\right)^2}{\dot{m}_\mathrm{p}h_\mathrm{LHV}} = \frac{\tfrac{1}{2}\left(v_\mathrm{e}^2+v_0^2\right)}{h_\mathrm{LHV}}$$
$$\eta_\mathrm{tp} \equiv \eta_\mathrm{t}\eta_\mathrm{p} = \frac{Fv_0}{\Delta\dot{E}_\mathrm{source}} = \frac{Fv_0}{\dot{m}_\mathrm{p}h_\mathrm{LHV}} = \frac{v_0}{c_\mathrm{sp}h_\mathrm{LHV}} = \frac{v_0 g}{h_\mathrm{LHV}}I_\mathrm{sp} \tag{16}$$

where the $\tfrac{1}{2}\dot{m}_\mathrm{p}v_0^2$ in the denominator corresponds to the initial kinetic energy of the propellant exhausted in the fix reference frame, always negligible ($\tfrac{1}{2}\dot{m}_\mathrm{p}v_0^2 << \Delta\dot{E}_\mathrm{source}$); specific fuel consumption, $c_\mathrm{sp}$, and specific impulse, $I_\mathrm{sp}$, are studied below. The global energy balance in both, the moving frame and the fix frame may further clarify this term:

$$\text{Energy balance in moving frame:}\quad \dot{m}_\mathrm{f}h_\mathrm{LHV} = \dot{m}_\mathrm{f}c_p\left(T_\mathrm{e}-T_f\right)+\tfrac{1}{2}\dot{m}_\mathrm{f}v_\mathrm{e}^2$$
$$\text{Energy balance in fixed frame:}\quad \tfrac{1}{2}\dot{m}_\mathrm{f}v_0^2+\dot{m}_\mathrm{f}h_\mathrm{LHV} = \dot{m}_\mathrm{f}c_p\left(T_\mathrm{e}-T_\mathrm{f}\right)+Fv_0+\tfrac{1}{2}\dot{m}_\mathrm{f}\left(v_\mathrm{e}-v_0\right)^2 \tag{17}$$

which, with $F=\dot{m}_\mathrm{p}v_\mathrm{e}$, coincide. The rocket engine has very high thermal efficiency, typically $\eta_\mathrm{t}$=0.7..0.8 because gases in the chamber are very hot, and they exit very cold from the converging/diverging nozzle (e.g. at 3000 K and 300 K, respectively). Also notice that engine efficiency grows with flight speed (and with exit speed, of course).

Thrust in a rocket $F=\dot{m}_\mathrm{p}v_\mathrm{e}$ does not depends on advancing speed $v_0$, but the $\Delta v$ due to a given amount of propellant increases with advancing speed in the form $\Delta v\sqrt{1+2v_0/\Delta v}$ because of the higher absolute kinetic energy of propellant, what is known as Oberth effect, showing that it is better to accelerate spacecraft at periapsis (when the speed is higher); this effect is negligible for long-lasting low-propellant-flow-rate rockets.

Notice by the way that there is no direct correlation between thrust an power; thrust is a force that may or may not do work (i.e. produce power), whereas power is the rate of energy delivered or consumed, which in the propulsion field may refer to propulsion power, $Fv_0$ (which is proportional to speed), or to mechanical energy transmitted by a shaft (or to the working fluids), or even to thermal power developed from chemical reactions.

**Specific fuel consumption. Specific thrust. Specific impulse**

"Specific", for a quantity A, refers to its value per unit of another quantity B, and is written 'B specific A' except in the most usual case of mass-specific quantities, where B can be omitted to simply say 'specific A'; e.g. thrust specific fuel-rate means $\dot{m}_{\mathrm{f}}/F$, and specific power means mass specific power, $\dot{W}/m$. Another way to say 'B specific A' is to say 'B-unitary A' (e.g. thrust-unitary fuel-rate means $\dot{m}_{\mathrm{f}}/F$).

In the field of propulsion, however, the term 'specific A' does not means 'mass specific A', but a more general 'B specific A' with quantity B assumed to be understood by all the users. The following cases are most important.

- Specific thrust, $F_{\mathrm{sp}}$, might refer to 'engine-mass specific thrust', $F/m_{\mathrm{eng}}$, but in aero-engines it really refers to 'air-mass-flow-rate specific thrust', $F/\dot{m}_{\mathrm{a}}$. To quantify the former parameter ($F/m_{\mathrm{eng}}$), it seems wiser to exchange mass by weight-on-Earth in the definition ($W=mg$, with $g$=9.8 m/s$^2$), to have a non-dimensional parameter, $F/W$, and use the term 'thrust-to-weight ratio', instead of the ambiguous 'specific thrust' or even the correct one 'weight specific thrust'. The name 'specific thrust' ($F/\dot{m}_{\mathrm{a}}$) is only used in air-breathing engines (basically in turbofans), because the same concept of 'propellant-rate specific thrust', $F/\dot{m}_{\mathrm{p}}$ (the propellant being basically air in turbofans) is not named specific thrust but (modified) specific impulse (see below). In conclusion:

$$F_{\mathrm{sp}} \equiv \frac{F}{\dot{m}_{\mathrm{a}}} \quad \text{(usually in units of kN/(kg/s), with a typical value of 60 kN/(kg/s))} \qquad (1)$$

- Specific impulse, $I_{\mathrm{sp}}$, as for specific thrust just discussed, is not intended to be the impulse per unit mass, $J/m$, where $J\equiv\int F\mathrm{d}t$ is the impulse (i.e. the change in linear momentum of a body, $J\equiv\int F\mathrm{d}t=\int \mathrm{d}(mv)=\Delta(mv)$, often with symbol $I$ instead of $J$); in propulsion, specific impulse refers to 'on-board-propellant-weight-flow-rate specific impulse':
  - For air-breathing engines:

$$I_{\mathrm{sp}} \equiv \frac{F}{\dot{m}_{\mathrm{f}} g} \quad \text{(in [s], with typical values of 6000 s for turbofans)} \qquad (2)$$

  - For rocket engines:

$$I_{\mathrm{sp}} \equiv \frac{F}{\dot{m}_{\mathrm{p}} g} \quad \text{(in [s], with typical values of 300 s for chemical rockets)} \qquad (3)$$

The specific impulse is a measure of how well the spent propellant is used in providing thrust, and thus, in air-breathing engines the spent propellant is taken to be just the fuel ($\dot{m}_{\mathrm{f}}$) and not the whole mass-flow-rate ($\dot{m}_\mathrm{a}+\dot{m}_\mathrm{f}\approx\dot{m}_\mathrm{a}$), i.e. the costly propellant, since in this case air is a free oxidiser not carried aboard. It would had been more natural to define specific impulse as the impulse the propellant yields (the change in linear momentum of the body, d($mv$)) per unit mass of propellant used (−d$m_\mathrm{p}$), i.e. $I_\mathrm{sp}\equiv F/\dot{m}_\mathrm{p}$ in units of N/(kg/s), but the simplification brought by the definition (2) in units of time, using the second [s] in both the metric and the imperial system, is an undisputable advantage we all acknowledge and that is why we have adhered to it here. However, it happens that in rockets (where $F=\dot{m}_\mathrm{p}v_\mathrm{e}+\left(p_\mathrm{e}-p_0\right)A_\mathrm{e}\approx\dot{m}_\mathrm{p}v_\mathrm{e}$), the more natural definition $I_\mathrm{sp}\equiv F/\dot{m}_\mathrm{p}$ would have a simple and relevant meaning: $I_\mathrm{sp}\equiv F/\dot{m}_\mathrm{p}\approx v_\mathrm{e}$, i.e. coincides the exit speed of the propellant (in [m/s]) in adapted nozzles, and is very approximate in all cases, whereas the time units in the more usual definition (2) in [s] has no 'temporal' meaning; unfortunately, the variety of speed units in use worldwide is still a handicap that makes (2) preferable. In rocketry, the total impulse $J\equiv\int F\mathrm{d}t=\Delta(mv)=\int\dot{m}_\mathrm{p}v_\mathrm{e}\mathrm{d}t$, in [N·s], is also used sometimes.

- Specific fuel consumption (often with the symbol $c_\mathrm{sp}$), is defined differently for shaft and jet engines. When dealing with shaft-power engines, $c_\mathrm{sp}$ refers to 'break specific fuel consumption' (BSFC) defined as BSFC=SFC=$c_\mathrm{sp}\equiv\dot{m}_\mathrm{f}/\dot{W}_\mathrm{shaft}$. When dealing with jet-power engines (turbojets and rockets), $c_\mathrm{sp}$ refers to 'thrust specific fuel consumption' (TSFC) defined as TSFC=SFC=$c_\mathrm{sp}\equiv\dot{m}_\mathrm{f}/F$, where we have used 'f' to mean 'fuel' in air-breathing engines, and to mean 'propellant (fuel+oxidiser) in rocket engines. Notice that we use acronyms in upper case, e.g. SFC, and not sfc (or far for 'fuel to air ratio', and the like). The inverse of TSFC, $1/c_\mathrm{sp}=F/\dot{m}_\mathrm{f}$, when measured in terms of weight-rate instead of mass-rate, coincides with the specific impulse $I_\mathrm{sp}=F/\left(\dot{m}_\mathrm{f}g\right)$; see above. In summary, for all kind of jet engines (rockets and turbofans, using 'f' for the paid propellant):

$$TSFC\equiv\frac{\dot{m}_\mathrm{f}}{F}=\frac{1}{gI_\mathrm{sp}}\quad\text{(usually in units of (g/s)/kN)}\tag{4}$$

  - In rocket engines, $I_\mathrm{sp}$ is the preferred variable instead of TSFC, and both are directly related to propellant exit speed:

    $$v_\mathrm{e}=\frac{F}{\dot{m}_\mathrm{p}}=\frac{1}{TSFC}=gI_\mathrm{sp}\tag{5}$$

    e.g. Ariane 5 1st stage engine (Vulcain), has a specific impulse under vacuum of $I_\mathrm{sp}$=430 s, hence gases exhaust at about $v_\mathrm{e}=gI_\mathrm{sp}$=4200 m/s, and TSFC is $c_\mathrm{sp}$=1/4200 (kg/s)/N=240 (g/s)/kN).
  - In air-breathing engines, TSFC is the preferred variable instead of $I_\mathrm{sp}$, and it is related to specific thrust, $F_\mathrm{sp}$, and exit speed, $v_\mathrm{e}$, by:

$$TSFC\equiv c_\mathrm{sp}\equiv\frac{\dot{m}_\mathrm{f}}{F}=\frac{\dot{m}_\mathrm{f}}{\dot{m}_\mathrm{a}}\frac{\dot{m}_\mathrm{a}}{F}=\frac{1}{AF_\mathrm{sp}}=\frac{1}{A_\mathrm{c}\left[v_\mathrm{ec}-v_0+\beta\left(v_\mathrm{ef}-v_0\right)\right]}\tag{6}$$

where the case of a turbofan with bypass ratio $\beta \equiv \dot{m}_\mathrm{f}/\dot{m}_\mathrm{c}$ is presented in the last of (6), with an air/fuel ratio in the core stream $A_c=A/(1+\beta)$, and exhaust speeds in the core and the fan streams of $v_{ec}$ and $v_{ef}$, respectively. The relationship with the global (thermo-propulsive) efficiency of the jet engine, $\eta_{tp}$, (12) is (see Efficiency, above):

$$\eta_\mathrm{tp}=\eta_t\eta_\mathrm{p}=\frac{Fv_0}{\Delta\dot{E}_\mathrm{source}}=\frac{v_0}{\dfrac{\dot{m}_\mathrm{f}}{F}h_\mathrm{LHV}}=\frac{F_\mathrm{sp}Av_0}{h_\mathrm{LHV}}=\frac{gI_\mathrm{sp}v_0}{h_\mathrm{LHV}}=\frac{v_0}{c_\mathrm{sp}h_\mathrm{LHV}} \tag{7}$$

e.g. for a typical turbofan with a TSFC value of $c_{sp}$=16 (g/s)/kN, the overall engine efficiency is $\eta_{tp}=v_0/(c_{sp}\cdot h_{LHV})=250/(16\cdot10^{-6}\cdot43\cdot10^6)=0.36$, where $h_{LHV}$=43 MJ/kg for Jet A-1; i.e. 6% of the fuel lower-heating-value is directly used for the advance (the rest goes with the hot and accelerated jet exhaust). The corresponding specific impulse is $I_{sp}=1(gc_{sp})=1/(9.8\cdot16\cdot10^{-6})=6400$ s (but notice that the exhaust speed is not $v_e=gI_{sp}$=63 000 m/s but around 290 m/s). Turbofan efficiency is increasing by higher thermal efficiencies, $\eta_t$ (only dependent on the core stream), increasing working temperatures (turbine entry temperature, TET), increasing working pressures (overall pressure ratio, OPR), and by increasing propulsion efficiency, $\eta_p$ (mostly dependent on the fan stream for high bypass ratio turbofans) by using larger fans, spinning at lower speeds, with lower fan pressure ratio (reduction gears may be needed). Minimum theoretical TSFC for a turbofan at cruise can be estimated if we assume a maximum of $\eta_t$=0.6 from thermodynamics practice, and a maximum of $\eta_p$=0.9 from turbomachinery practice: for a cruise speed of $v_0$=250 m/s ($M$=0.85 at 11 km altitude), $c_{sp}=v_0/(\eta_t\eta_p h_{LHV})=250/(0.6\cdot0.9\cdot43\cdot10^6)=$ 11 (g/s)/kN, showing that there is still margin to improvements from the current $c_{sp}$=16 (g/s)/kN.

In general transport business, specific fuel consumption is often stated in mass of fuel per passenger per km (i.e. kg/pkm), or per 100 km (in [kg/p100km]), and many times in fuel volume instead of fuel mass (in [L/p100km]). With a TSFC of $c_{sp}$=15.5 (g/s)/kN, a fully loaded A380 consumes 3 kg/p100km (i.e. 3 kg of fuel per passenger every 100 km), a little less than a car with just the driver (4 kg/p100km), and almost triple than modern rail or boat transport (about 1 kg/p100km). In terms of energy per passenger per km (Jet A-1 has $h_{LHV}$=43 MJ/kg), the A380 consumes (43 MJ/kg)·(0.03 kg/pkm)=1.3 MJ/pkm. To avoid stating the 'fully loaded' condition, costs are often stated as per seat (instead of per person). For freight, tonnes (rarely kg) are used instead of passengers.

Exercise 1. Find the specific fuel consumption in kg of fuel per pax per 100 km of an A380, knowing that the thrust specific fuel consumption of its engines at cruise is $c_{sp}$=15.5 (g/s)/kN, and that it is powered by four engines each with a cruise thrust of 90 kN, carrying 650 passengers at 900 km/h.

Sol.: With total thrust $F$=4×80=320 kN and TSFC of 15.5 (g/s)/kN, we get $\dot{m}_{f,cruise}$ =15.5·320=4960 g/s=18 000 kg/h, which at $v_0$=900 km/h means a fuel consumption of 18000/900=20 kg/km, or 2000 kg every 100 km, which shared among the 650 pax finally yields

2000/650=3.1 kg/p100km. This value can be easily stated per volume of fuel knowing that for Jet A-1 $\rho$=810 kg/m$^3$.

**Other figures of merit in propulsion**

We have seen the main absolute variable of an engine: thrust, or power, and the energy ratio of power delivered versus input power, i.e. propulsion efficiencies (propeller, engine, and overall propulsion efficiencies). We have also seen the three basic 'specific' parameters: specific fuel consumption, specific thrust, and specific impulse. We present here a structured summary while adding some other figures of merit for internal combustion engines (both, engines providing shaft power like reciprocating ICE and turboprops, and for engines providing jet power like turbofans and rockets).

- Engine-size related:
  - In shaft-engines
    - Engine power, $\dot{W}_{\text{shaft}}$, usually measured on bench by a braking system (tachometer and torque-meter). Often, shaft speed for maximum power is also given, and sometimes, maximum torque and corresponding shaft speed are given too (the power maximum occurs at higher rotation rates).
    - Engine mass, $m_{\text{eng}}$, and overall dimensions.
    - Specific power (at full power): $\dot{W}_{\text{shaft}} / m_{\text{eng}}$, usually in kW/kg, or its inverse, power-unitary mass, $m_{\text{eng}} / \dot{W}_{\text{shaft}}$. The first aircraft engine (Flyer-I, 1903) had 9/80=0.11 kW/kg, whereas a modern car engine (gasoline or diesel) may have 0.4 kW/kg, a large turboshaft may have 45 000 / 900=5 kW/kg, and a Formula-One racing car engine may reach 6 kW/kg (in comparison, turbojet engines may reach 20 kW/kg).
  - In jet-engines
    - Engine thrust (at full power), $F$, usually measured on bench by load cells on engine supports.
    - Engine mass, $m_{\text{eng}}$, and overall dimensions.
    - Thrust to weight ratio (at maximum thrust): $F/(m_{\text{eng}}g)$ (written $F/W$), or its inverse the weight to thrust ratio: $m_{\text{eng}}g/F$. Modern turbofans like RR-Trent 900, with $F$=350 kN and $m$=6300 kg, have $F/(m_{\text{eng}}g)$=350/(6.3·9.8)=5.5 (in comparison, the first aircraft engine (Flyer-I, 1903) had a thrust of some 600 N and $m_{eng}$=80 kg, so that $F/(m_{\text{eng}}g)$=600/(80·9.8)=0.76).
- Fuel-consumption related:
  - In shaft engines
    - Power-unitary fuel consumption, $c_{\text{sp}}=\dot{m}_{\text{f}} / \dot{W}_{\text{shaft}}$ usually in (g/s)/kW or in g/kWh, commonly called brake specific fuel consumption, BSFC, or simply SFC.
    - Fuel-flow-rate specific power: $\dot{W}_{\text{shaft}} / \dot{m}_{\text{f}}$, either in kW/(g/s) or in kWh/g. This is the inverse of the former, and both are related to engine efficiency by (9).
  - In jet engines
    - Thrust-unitary fuel consumption, $c_{\text{sp}}=\dot{m}_{\text{f}} / F$ usually in (g/s)/kN, commonly called thrust specific fuel consumption, TSFC, or simply SFC. In rockets, 'fuel' means propellant (i.e. fuel plus oxidiser). Its inverse, when evaluated in fuel-weight units

instead of fuel-mass units, is the specific impulse, $I_{\text{sp}} \equiv F/(\dot{m}_{\text{f}}g)$, and both are related to engine efficiency by (12) or (16).

- Other figures of merit are: engine price, lifespan, mean-time between overhauls, type of fuel required, frontal area, safety in operation, vibrations, noise, pollution... Engine emissions have been greatly reduced in last decades, and strict limits are being imposed, but there is still a big problem of $NO_x$ and soot-particle contamination in dense-traffic areas (mainly by city traffic, but aviation is taking its share; e.g. see Aviation fuel consumption and emissions, aside).

## PROPULSION SYSTEMS

The major application of propulsion (pushing forward to make a body moving against natural forces) is for transportation of people and goods, over land, sea, undersea, air, and into space. There are some vehicles able to through several media (e.g. land and water, air and space).

### TERRESTRIAL PROPULSION

Propulsion is needed for land vehicles (on roadways, railways, and off-road), and for the land-phase of other vehicles (e.g. aircraft rolling, take-off, landing, spacecraft rovers...). The two main propulsion systems on land are:

- For road and off-road vehicles, a reciprocating IC engine with a fuel tank (diesel or gasoline), and pneumatics (rubber wheels) for friction traction.
- For trains, several electrical motors fed from a catenary cable (or a third rail), and a steel wheels on steel rails for friction traction.

Aircraft and space rovers have rubber-wheels too, although the first aircraft (Flyer-1, 1903) had no wheels; it took off on a monorail (using a detachable trolley), and landed on large skids, with thrust being provided by an air propeller.

### MARINE PROPULSION

On water and underwater. The typical propulsion system is a diesel engine and screw propeller.

### AIRCRAFT PROPULSION

The typical propulsion system is a turbofan engine (a kind of gas turbine with a ducted fan as main thruster).

### SPACE PROPULSION

Launchers, space rockets, descent and landing. The typical propulsion system is a rocket engine (a combustion chamber and a propulsive nozzle).

### NOZZLES

Nozzle flow (for propulsion or non-propulsion applications).

### PROPELLERS

Propellers for aircraft, marine, or land applications.

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