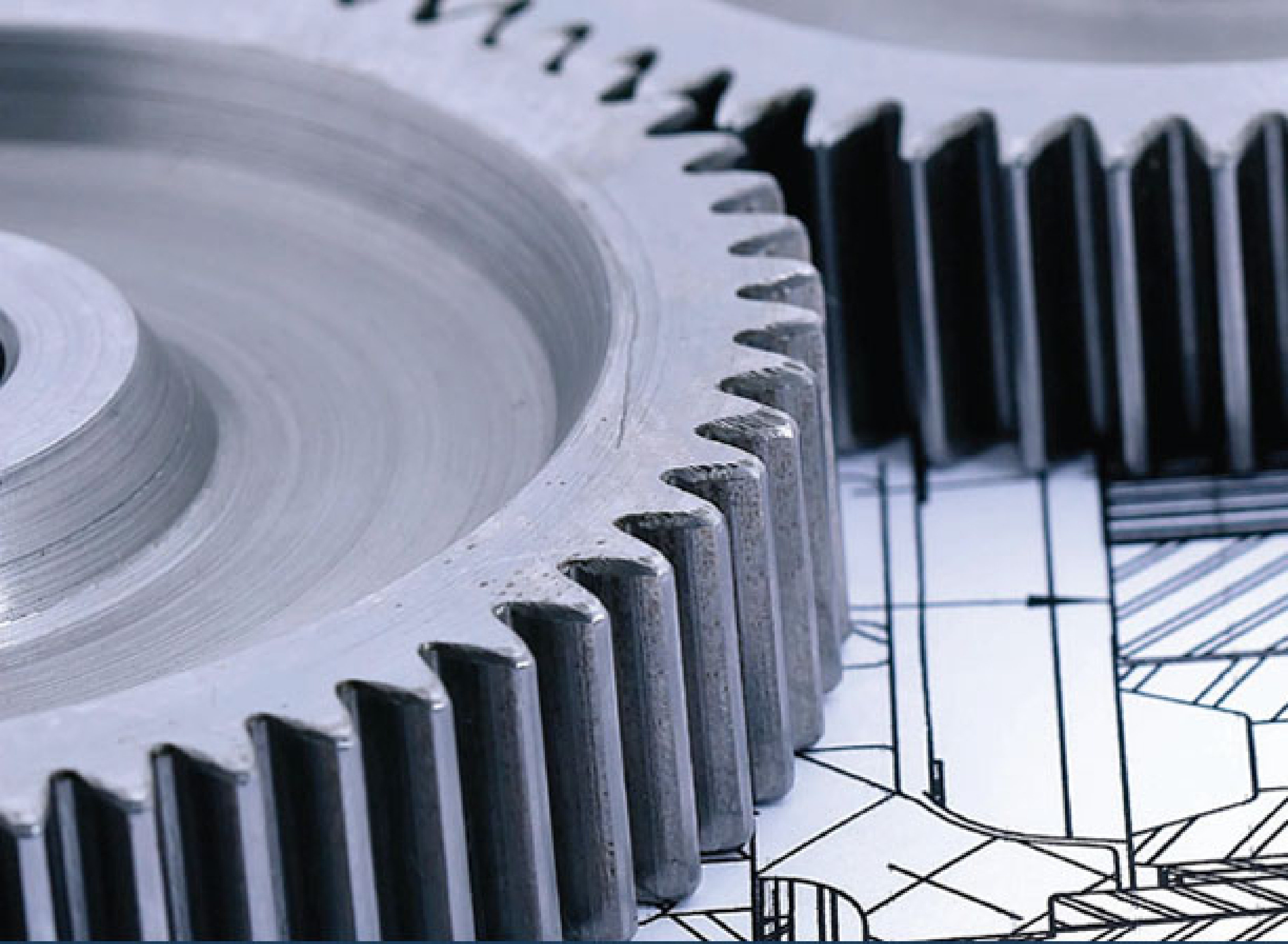

Engineering Ratios

Mindi Harms

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Chapter 1

Air-Fuel Ratio

Air-fuel ratio (**AFR**) is the mass ratio of air to fuel present during combustion. If exactly enough air is provided to completely burn all of the fuel, the ratio is known as the stoichiometric mixture (often abbreviated to **stoich**). AFR is an important measure for anti-pollution and performance tuning reasons. Lambda (λ) is an alternative way to represent AFR.

stoichiometric mixture fraction The relative amounts of oxygen enrichment and fuel dilution can be quantified by the stoichiometric mixture fraction, Zst, defined as Zst=(1+YF,0WOvO/YO,0WFvF)−1, where YF,0 and YO,0 represent the fuel and oxidizer mass fractions at the inlet, WF and WO are the species molecular weights, and vF and vO are the fuel and oxygen stoichiometric coefficients, respectively.

In industrial fired heaters, power plant steam generators, and large gas-fired turbines, the more common term is **percent excess combustion air**. For example, excess combustion air of 15 percent means that 15 percent more than the required stoichiometric air is being used.

A stoichiometric mixture is the working point that modern engine management systems employing fuel injection attempt to achieve in light load cruise situations. For gasoline fuel, the stoichiometric air/fuel mixture is approximately 14.7; i.e. the approximate mass of air is 14.7 mass of fuel. Any mixture less than 14.7 to 1 is considered to be a rich mixture, any more than 14.7 to 1 is a lean mixture - given perfect (ideal) "test" fuel (gasoline consisting of solely n-heptane and iso-octane). In reality, most fuels consist of a combination of heptane, octane, a handful of other alkanes, plus additives including detergents, and possibly oxygenators such as MTBE (methyl tert-butyl ether) or ethanol/methanol. These compounds all alter the stoichiometric ratio, with most of the additives pushing the ratio downward (oxygenators bring extra oxygen to the combustion event in liquid form that is released at time of combustions; for MTBE-laden fuel, a stoichiometric ratio can be as low as 14.1:1). Vehicles using an oxygen sensor(s) or other feedback-loop to control fuel to air ratios (usually by controlling fuel volume) will usually compensate automatically for this change in the fuel's stoichiometric rate by measuring the exhaust gas composition, while vehicles without such controls (such as most motorcycles until recently, and cars predating the mid-1980s) may have difficulties running certain boutique blends of fuels (esp. winter fuels used in some areas) and may need to be rejetted (or otherwise have the fueling ratios altered) to compensate for special boutique fuel mixes. Vehicles using oxygen sensors enable the air-fuel ratio to be monitored by means of an air fuel ratio meter.

Synopsis

In theory a stoichiometric mixture has just enough air to completely burn the available fuel. In practice this is never quite achieved, due primarily to the very short time available in an internal combustion engine for each combustion cycle. Most of the combustion process completes in approximately 4-5 milliseconds at an engine speed of 6000 rpm. This is the time that elapses from when the spark is fired until the burning of the fuel air mix is essentially complete after some 80 degrees of crankshaft rotation.

Catalytic converters are designed to work best when the exhaust gases passing through them show nearly perfect combustion has taken place.

A stoichiometric mixture unfortunately burns very hot and can damage engine components if the engine is placed under high load at this fuel air mixture. Due to the high temperatures at this mixture, detonation of the fuel air mix shortly after maximum cylinder pressure is possible under high load (referred to as knocking or pinging). Detonation can cause serious engine damage as the uncontrolled burning of the fuel air mix can create very high pressures in the cylinder. As a consequence stoichiometric mixtures are only used under light load conditions. For acceleration and high load conditions, a richer mixture (lower air-fuel ratio) is used to produce cooler combustion products and thereby prevent detonation and overheating of the cylinder head.

In the typical air to natural gas combustion burner, a double cross limit strategy is employed to ensure ratio control. (This method was used in World War 2). The strategy involves adding the opposite flow feedback into the limiting control of the respective gas (air or fuel).This assures ratio control within an acceptable margin.

Other terms used

There are other terms commonly used when discussing the mixture of air and fuel in internal combustion engines.

Mixture

Mixture is the predominant word that appears in training texts, operation manuals and maintenance manuals in the aviation world.

AFR

The **Air fuel ratio** is the most common reference term used for mixtures in internal combustion engines.

$$AFR = \frac{m_{air}}{m_{fuel}}$$

It is the ratio between the *mass* of air and the mass of fuel in the fuel-air mix at any given moment.

For pure octane the stoichiometric mixture is approximately 14.7:1 or λ of 1.00 exactly.

In naturally aspirated engines powered by octane, maximum power is frequently reached at AFRs ranging from 12.5 - 13.3:1 or λ of 0.850 - 0.901.

FAR

Fuel Air ratio is commonly used in the gas turbine industry as well as in government studies of internal combustion engine and refers to the ratio of fuel to the air, it is 1/AFR.

Lambda

Most practical AFR devices actually measure the amount of residual oxygen (for lean mixes) or unburnt hydrocarbons (for rich mixtures) in the exhaust gas. Lambda (λ) is the ratio of actual AFR to stoichiometry for a given mixture. Lambda of 1.0 is at stoichiometry, rich mixtures are less than 1.0, and lean mixtures are greater than 1.0.

There is a direct relationship between lambda and AFR. To calculate AFR from a given lambda, multiply the measured lambda by the stoichiometric AFR for that fuel. Alternatively, to recover lambda from an AFR, divide AFR by the stoichiometric AFR for that fuel. This last equation is often used as the definition of lambda:

$$\lambda = \frac{AFR}{AFR_{stoich}}$$

Because the composition of common fuels varies seasonally, and because many modern vehicles can handle different fuels, when tuning, it makes more sense to talk about lambda values rather than AFR.

Equivalence ratio

The **equivalence ratio** of a system is defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio. Mathematically,

$$\phi = \frac{\text{fuel-to-oxidizer ratio}}{(\text{fuel-to-oxidizer ratio})_{st}} = \frac{m_{fuel}/m_{ox}}{(m_{fuel}/m_{ox})_{st}} = \frac{n_{fuel}/n_{ox}}{(n_{fuel}/n_{ox})_{st}}$$

where, *m* represents the mass, *n* represents number of moles, suffix *st* stands for stoichiometric conditions.

stoichiometric mixture fraction

$Zst = \lambda / (1 + \lambda)$

The advantage of using equivalence ratio over fuel-to-oxidizer ratio is that it does not have the same dependence as fuel-to-oxidizer ratio on the units being used. For example fuel-to-oxidizer ratio based on mass of fuel and oxidizer is not same as one define based on number of moles. This is not the case for equivalence ratio. The following example can help clarify the point. Consider a mixture of one mole of ethane (C_2H_6) and one mole of oxygen (O_2).

fuel-to-oxidizer ratio of this mixture based on the mass of fuel and air is

$$\frac{m_{C_2H_6}}{m_{O_2}} = \frac{1 \cdot (2 \cdot 12 + 6 \cdot 1)}{1 \cdot (2 \cdot 16)} = \frac{30}{32} = 0.938$$

fuel-to-oxidizer ratio of this mixture based on the number of moles of fuel and air is $\frac{n_{C_2H_6}}{n_{O_2}} = \frac{1}{1} = 1.$

Clearly the two values are not equal. To compare it to the equivalence ratio, we need to determine the fuel-to-oxidizer ratio of ethane and oxygen mixture. For this we need to consider the stoichiometric reaction of ethane and oxygen,

$$C_2H_6 + \tfrac{7}{2}O_2 \rightarrow 2CO_2 + 3H_2O$$

This gives,

$$(\text{fuel-to-oxidizer ratio based on mass})_{st} = \left(\frac{m_{C_2H_6}}{m_{O_2}}\right)_{st} = \frac{1 \cdot (2 \cdot 12 + 6 \cdot 1)}{3.5 \cdot (2 \cdot 16)} = \frac{30}{112} = 0.268$$

$$(\text{fuel-to-oxidizer ratio based on number of moles})_{st} = \left(\frac{n_{C_2H_6}}{n_{O_2}}\right)_{st} = \frac{1}{3.5} = 0.286$$

Thus we can determine the equivalence ratio of the give mixture as,

$$\phi = \frac{m_{C_2H_6}/m_{O_2}}{(m_{C_2H_6}/m_{O_2})_{st}} = \frac{0.938}{0.268} = 3.5$$

or equivalently as,

$$\phi = \frac{n_{C_2H_6}/n_{O_2}}{(n_{C_2H_6}/n_{O_2})_{st}} = \frac{1}{0.286} = 3.5$$

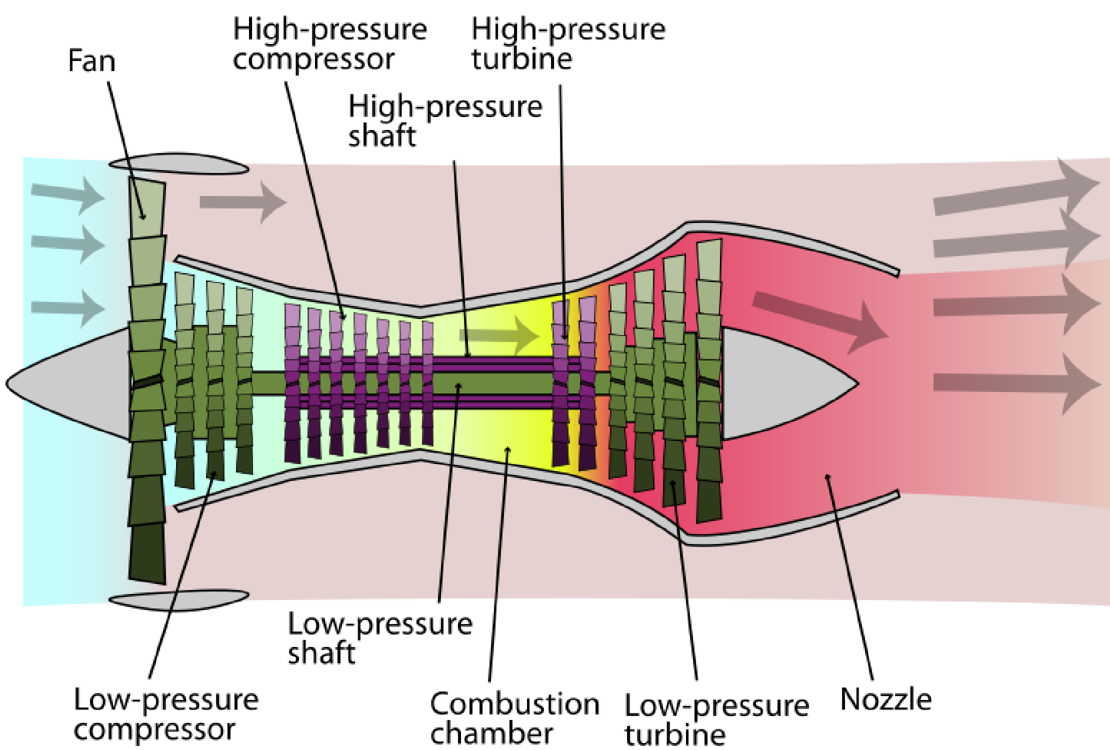
Another advantage of using the equivalence ratio is that ratios greater than one always represent excess fuel in the fuel-oxidizer mixture than would be required for complete combustion (stoichiometric reaction) irrespective of the fuel and oxidizer being used, while ratios less than one represent a deficiency of fuel or equivalently excess oxidizer in the mixture. This is not the case if one uses fuel-to-oxidizer ratio, which will take different values for different mixtures.

Equivalence ratio is related to λ (defined previously) as follows,

$$\phi = \frac{1}{\lambda}$$

Chapter 2

Bypass Ratio



Schematic turbofan engines; the high-bypass engine (lower) has a large fan that routes much air around the turbine, the low-bypass engine (upper) has a smaller fan routing more air into the turbine.
The bypass air is shown in pink, whilst the core gases are shown in red.

The term **bypass ratio (BPR)** relates to the design of turbofan engines, commonly used in aviation. It is defined as the ratio between the mass flow rate of air drawn in by the fan bypassing the engine core to the mass flow rate passing through the engine core.

A high bypass ratio gives a lower (actual) exhaust speed. This reduces the thrust specific fuel consumption, but reduces the top speed and gives a heavier engine.

A lower bypass ratio gives a higher exhaust speed, which is needed to sustain higher, usually supersonic, airspeeds. This increases the thrust specific fuel consumption.

In spite of this, it turns out that for jet engines in general, at optimum bypass ratios, the fuel burnt to travel any particular *distance* is largely independent of airspeed, but with supersonic jet engines being slightly more efficient in practice, at their design point.

Description

Jet engines are generally able to create considerably more energy than they can use in moving air through the engine core. This is because the limiting factor is the temperature at the turbine face, and that is a function of the total amount of fuel burned. Increasing airflow, and thus thrust, would imply burning more fuel and generating higher temperatures. It is possible to increase the airflow by burning "too much" fuel or adding water in front of the turbine to cool it, but both methods lead to incomplete combustion and very poor fuel efficiency. This was nevertheless commonly practiced in early jet engines because of a need to produce added thrust on takeoff. This is also why the exhaust plumes of older aircraft produce so much visible smoke (which is nothing more than unburned carbon from wasted jet fuel).

Rolls–Royce came up with a better use of the extra energy in their Conway turbofan engine, developed in the early 1950s. In the Conway, an otherwise normal axial-flow turbojet was equipped with an oversized first compressor stage (the one closest to the front of the engine), and centered inside a tubular nacelle (in effect, a ducted fan arrangement). While the inner portions of the compressor worked "as normal" and provided air into the core of the engine, the outer portion blew air around the engine to provide extra thrust. The Conway had a very small bypass ratio of only 0.3, but the improvement in fuel economy was notable; as a result, it and its derivatives like the Spey became some of the most popular jet engines in the world.

If the fan of a turbofan engine drives two kilograms of air around the engine for every kilogram that passes through the engine's core, the engine is said to have a bypass ratio of 2 (or 2 to 1). Higher bypass ratios generally give better Thrust specific fuel consumption as an increasing amount of thrust is being generated without burning more fuel. This is achieved since the engine propels a larger amount of air rearwards at slower speed, rather than a smaller amount of air at higher speed- because thrust is the momentum given to the air per second the thrust is the same. However energy is a square law on speed, and so it takes less energy to generate the same thrust; and hence less fuel is needed, the specific fuel consumption reduces.

Thus, with the example, for engines with the same thrust, the fuel efficiency would be improved by something less than 50%.

High bypass ratios are also correlated with lower noise, since the large flow of air surrounding the jet exhaust from the engine core helps to buffer the noise produced by the latter.

Through the 1960s the bypass ratios grew, making jetliners competitive in fuel terms with piston-powered planes for the first time. Most of the very-large engines in this class were pioneered in the United States by both Pratt & Whitney and General Electric, which for the first time was out-competing the United Kingdom in engine design. Rolls-Royce also started the development of the high-bypass turbofan, and although it caused considerable trouble at the time, the RB.211 would go on to become one of their most successful products.

Turbofans are typically broken into one of two categories: low–bypass and high–bypass ratio. In a low–bypass turbofan, only a small amount of air passes through the fan ducts and the fan is of very small diameter. The fan in a high–bypass turbofan is much larger to force a large volume of air through the ducts. The low–bypass turbofan is more compact, but the high-bypass turbofan can produce much greater thrust, is more fuel efficient, and is much quieter.

Today, almost all jet engines include some amount of bypass. Lower bypass ratios are appropriate at high speeds because the exhaust velocity must exceed the airspeed to give forward net thrust. For lower speed operations, such as airliners, modern engines use bypass ratios up to 17, while for higher speed operations such as fighter aircraft the ratios are much lower, around 1.5; and around 0.5 for sustained speeds around Mach 2 and somewhat above.

At transonic and supersonic speeds, very high bypass ratios still present engineering challenges.

Engine bypass ratios

Engine	Aircraft	Bypass ratio
Rolls-Royce/Snecma Olympus 593	Concorde (turbojet)	0:1
Rolls-Royce Tay	Gulfstream IV, Fokker 70, Fokker 100	3.1:1
SNECMA M88	Dassault Rafale	0.30:1
Pratt & Whitney JT8D	DC-9, MD-80, Boeing 727, Boeing 737 100 and 200 series	0.96:1
Pratt & Whitney F100	F-16, F-15	0.34:1
General Electric F404	F/A-18, T-50, F-117, X-29, X-31	0.34:1
Eurojet EJ200	Eurofighter Typhoon	0.4:1
Klimov RD-33	MiG-29, Il-102	0.49:1
Saturn AL-31F	Su-27, Su-30, Chengdu J-10	0.59:1

Kuznetsov NK-321	Tu-160	1.4:1
PowerJet SaM146	Sukhoi Superjet 100	4.43:1
Pratt & Whitney PW2000	Boeing 757, C-17 Globemaster III	5.9:1
Progress D-436	Yak-42M, Beriev Be-200, An-148	6.2:1
General Electric GEnx	Boeing 787	8.5:1
Rolls-Royce Trent 900	Airbus A380	8.7:1
General Electric GE90	Boeing 777	9:1
Rolls-Royce Trent 1000	Boeing 787	11:1

Chapter 3

Compression Ratio

The **compression ratio** of an internal-combustion engine or external combustion engine is a value that represents the ratio of the volume of its combustion chamber from its largest capacity to its smallest capacity. It is a fundamental specification for many common combustion engines.

In a piston engine it is the ratio between the volume of the cylinder and combustion chamber when the piston is at the bottom of its stroke, and the volume of the combustion chamber when the piston is at the top of its stroke.

Picture a cylinder and its combustion chamber with the piston at the bottom of its stroke containing 1000 cc of air (900 cc in the cylinder plus 100 cc in the combustion chamber). When the piston has moved up to the top of its stroke inside the cylinder, and the remaining volume inside the head or combustion chamber has been reduced to 100 cc, then the compression ratio would be proportionally described as 1000:100, or with fractional reduction, a 10:1 compression ratio.

A high compression ratio is desirable because it allows an engine to extract more mechanical energy from a given mass of air-fuel mixture due to its higher thermal efficiency. High ratios place the available oxygen and fuel molecules into a reduced space along with the adiabatic heat of compression–causing better mixing and evaporation of the fuel droplets. Thus they allow increased power at the moment of ignition and the extraction of more useful work from that power by expanding the hot gas to a greater degree.

Higher compression ratios will however make gasoline engines subject to engine knocking if lower octane-rated fuel is used, also known as detonation. This can reduce efficiency or damage the engine if knock sensors are not present to retard the timing. However, knock sensors have been a requirement of the OBD-II specification used in 1996 model year vehicles and newer.

Diesel engines on the other hand operate on the principle of compression ignition, so that a fuel which resists autoignition will cause late ignition which will also lead to engine knock.

Formula

The ratio is calculated by the following formula:

$$\mathrm{CR} = \frac{\frac{\pi}{4} b^2 s + V_c}{V_c}$$, where

b= cylinder bore (diameter)

s= piston stroke length

V_c= clearance volume. It is the volume of the combustion chamber (including head gasket). This is the minimum volume of the space at the end of the compression stroke, i.e. when the piston reaches top dead center (TDC). Because of the complex shape of this space, it is usually measured directly rather than calculated.

Typical compression ratios

Petrol (gasoline) engine

Due to pinging (detonation), the compression ratio in a gasoline or petrol-powered engine will usually not be much higher than 10:1, although some production automotive engines built for high-performance from 1955–1972 had compression ratios as high as 13.0:1, which could run safely on the high-octane leaded gasoline then available.

A technique used to prevent the onset of knock is the high "swirl" engine that forces the intake charge to adopt a very fast circular rotation in the cylinder during compression that provides quicker and more complete combustion. Recently, with the addition of variable valve timing and knock sensors to delay ignition timing, it is possible to manufacture gasoline engines with compression ratios of over 11:1 that can use 87 MON (octane rating) fuel.

In engines with a 'ping' or 'knock' sensor and an electronic control unit, the CR can be as high as 13:1 (2005 BMW K1200S). In 1981, Jaguar released a cylinder head that allowed up to 14:1 compression; but settled for 12.5:1 in production cars. The cylinder head design was known as the "May Fireball" head; it was developed by a Swiss engineer Michael May.

Petrol/gasoline engine with pressure-charging

In a turbocharged or supercharged gasoline engine, the CR is customarily built at 9.32:1 or lower.

Petrol/gasoline engine for racing

Motorcycle racing engines can use compression ratios as high as 14:1, and it is not uncommon to find motorcycles with compression ratios above 12.0:1 designed for 86 or 87 octane fuel.

Ethanol and methanol engines

Ethanol and methanol can take significantly higher compression ratios than gasoline. Racing engines burning methanol and ethanol fuel often incorporate a CR of 14.5-16:1, with F1 engines coming closer to 17:1(which is very critical for maximizing volumetric/fuel efficiency at around 18000 rpm)

Gas-fueled engine

In engines running exclusively on LPG or CNG, the CR may be higher, due to the higher octane rating of these fuels.

Diesel engine

In an auto-ignition diesel engine, (no electrical sparking plug—the hot air of compression lights the injected fuel) the CR will customarily exceed 14:1. Ratios over 22:1 are common. The appropriate compression ratio depends on the design of the cylinder head. The figure is usually between 14:1 and 16:1 for direct injection engines and between 18:1 and 23:1 for indirect injection engines.

Fault finding and diagnosis

Measuring the compression pressure of an engine, with a pressure gauge connected to the spark plug opening, gives an indication of the engine's state and quality. There is, however, no formula to calculate compression ratio based on cylinder pressure.

If the nominal compression ratio of an engine is given, the pre-ignition cylinder pressure can be estimated using the following relationship:

$$p = p_0 \times \mathrm{CR}^\gamma$$

where $p_0$is the cylinder pressure at bottom dead center which is usually at 1 atm, CR is the compression ratio, and $\gamma$is the specific heat ratio for the working fluid, which is about 1.4 for air, and 1.3 for methane-air mixture.

For example, if an engine running on gasoline has a compression ratio of 10:1, the cylinder pressure at top dead center is

$$p_{\mathrm{TDC}} = 1\ \mathrm{bar} \times 10^{1.4} = 25.1\ \mathrm{bar}$$

This figure, however, will also depend on cam (i.e. valve) timing. Generally, cylinder pressure for common automotive designs should at least equal 10 bar, or, roughly estimated in pounds per square inch (psi) as between 15 and 20 times the compression ratio, or in this case between 150 psi and 200 psi, depending on cam timing. Purpose-built racing engines, stationary engines etc. will return figures outside this range.

Factors including late intake valve closure (relatively speaking for camshaft profiles outside of typical production car range, but not necessarily into the realm of competition engines) can produce a misleadingly low figure from this test. Excessive connecting rod clearance, combined with extremely high oil pump output (rare but not impossible) can sling enough oil to coat the cylinder walls with enough oil to facilitate reasonable piston ring seal artificially give a misleadingly high figure, on engines with compromised ring seal.

This can actually be used to some slight advantage. If a compression test does give a low figure, and it has been determined it is not due to intake valve closure/camshaft characteristics, then one can differentiate between the cause being valve/seat seal issues and ring seal by squirting engine oil into the spark plug orifice, in a quantity sufficient to disperse across the piston crown and the circumference of the top ring land, and thereby effect the mentioned seal. If a second compression test is performed shortly thereafter, and the new reading is much higher, it would be the ring seal that is problematic, whereas if the compression test pressure observed remains low, it is a valve sealing (or more rarely head gasket, or breakthrough piston or rarer still cylinder wall damage) issue.

If there is a significant (greater than 10%) difference between cylinders, that may be an indication that valves or cylinder head gaskets are leaking, piston rings are worn or that the block is cracked.

If a problem is suspected then a more comprehensive test using a leak-down tester can locate the leak.

Saab variable-compression engine

Because cylinder bore diameter, piston stroke length and combustion chamber volume are almost always constant, the compression ratio for a given engine is almost always constant, until engine wear takes its toll.

One exception is the experimental Saab Variable Compression engine (SVC). This engine, designed by Saab Automobile, uses a technique that dynamically alters the volume of the combustion chamber (V_c), which, via the above equation, changes the compression ratio (CR).

To alter V_c, the SVC 'lowers' the cylinder head closer to the crankshaft. It does this by replacing the typical one-part engine block with a two-part unit, with the crankshaft in the lower block and the cylinders in the upper portion. The two blocks are hinged together at one side (imagine a book, lying flat on a table, with the front cover held an inch or so above the title page). By pivoting the upper block around the hinge point, the V_c (imagine the air between the front cover of the book and the title page) can be modified. In practice, the SVC adjusts the upper block through a small range of motion, using a hydraulic actuator.

Variable Compression Ratio (VCR) engines

The SAAB SVC is an advanced and workable addition to the world of VCR engines, the first being built and tested by Harry Ricardo in the 1920s. This work led to him devising the octane rating system that is still in use today. SAAB has recently been involved in working with the 'Office of Advanced Automotive Technologies', to produce a modern petrol VCR engine that showed an efficiency comparable with that of a Diesel. Many companies have been carrying out their own research in to VCR Engines, including Nissan, Volvo, PSA/Peugeot-Citroën and Renault but so far with no publicly demonstrated results.

The Atkinson cycle engine was one of the first attempts at variable compression. Since the compression ratio is the ratio between dynamic and static volumes of the combustion chamber the Atkinson cycle's method of increasing the length of the powerstroke compared to the intake stroke ultimately altered the compression ratio at different stages of the cycle.

Cortina Variable Compression engine

American inventor Paul Cortina is the latest entry into variable compression engine development. The Cortina engine is the only variable compression concept that slides the entire reciprocating assembly toward and away from the cylinder head. The advantage of this approach is that there is no complication to the workings of the reciprocating assembly itself, nor is there any complication outside of the engine. The way this is accomplished is by sliding the reciprocating assembly on a splined output shaft that is positioned perpendicular to a typical engine’s output orientation. The novel use of a barrel cam in place of a tradition crankshaft uses fewer parts than competing designs and adds the option of a true Atkinson cycle. It also has a more favorable leverage curve than a traditional crankshaft. Since the connecting rods stay straight, with a barrel cam cycling the pistons, it also is possible to box in the lower cylinder for use as an internal supercharger.

Dynamic compression ratio

The calculated compression ratio, as given above, presumes that the cylinder is sealed at the bottom of the stroke, and that the volume compressed is the actual volume.

However: intake valve closure (sealing the cylinder) always takes place after BDC, which may cause some of the intake charge to be compressed backwards out of the cylinder by the rising piston at very low speeds; only the percentage of the stroke after intake valve closure is compressed. Intake port tuning and scavenging may allow a greater mass of charge (at a higher than atmospheric pressure) to be trapped in the cylinder than the static volume would suggest (This "corrected" compression ratio is commonly called the "*dynamic compression ratio*".

This ratio is higher with more conservative (i.e., earlier, soon after BDC) intake cam timing, and lower with more radical (i.e., later, long after BDC) intake cam timing, but always lower than the static or "nominal" compression ratio.

The actual position of the piston can be determined by trigonometry, using the stroke length and the connecting rod length (measured between centers). The absolute cylinder pressure is the result of an exponent of the dynamic compression ratio. This exponent is a polytropic value for the ratio of variable heats for air and similar gases at the temperatures present. This compensates for the temperature rise caused by compression, as well as heat lost to the cylinder. Under ideal (adiabatic) conditions, the exponent would be 1.4, but a lower value, generally between 1.2 and 1.3 is used, since the amount of heat lost will vary among engines based on design, size and materials used, but provides useful results for purposes of comparison. For example, if the static compression ratio is 10:1, and the dynamic compression ratio is 7.5:1, a useful value for cylinder pressure would be $(7.5)^{1.3} \times$ atmospheric pressure, or 13.7 bar. ($\times$ 14.7 psi at sea level = 201.8 psi. The pressure shown on a gauge would be the absolute pressure less atmospheric pressure, or 187.1 psi.)

The two corrections for dynamic compression ratio affect cylinder pressure in opposite directions, but not in equal strength. An engine with high static compression ratio and late intake valve closure will have a DCR similar to an engine with lower compression but earlier intake valve closure.

Additionally, the cylinder pressure developed when an engine is running will be higher than that shown in a compression test for several reasons.

- The much higher velocity of a piston when an engine is running versus cranking allows less time for pressure to bleed past the piston rings into the crankcase.
- a running engine is coating the cylinder walls with much more oil than an engine that is being cranked at low RPM, which helps the seal.
- the higher temperature of the cylinder will create higher pressures when running vs. a static test, even a test performed with the engine near operating temperature.
- A running engine does not stop taking air & fuel into the cylinder when the piston reaches BDC; The mixture that is rushing into the cylinder during the downstroke develops momentum and continues briefly after the vacuum ceases (in the same respect that rapidly opening a door will create a draft that continues after movement of the door ceases). This is called scavenging. Intake tuning, cylinder head design, valve timing and exhaust tuning determine how effectively an engine scavenges.

Compression ratio versus overall pressure ratio

Compression ratio and overall pressure ratio are interrelated as follows:

Compression ratio	2:1	3:1	5:1	10:1	15:1	20:1	25:1	35:1
Pressure ratio	2.64:1	4.66:1	9.52:1	25.12:1	44.31:1	66.29:1	90.60:1	145.11:1

The reason for this difference is that compression ratio is defined via the volume reduction:

$$\mathrm{CR} = \frac{V_1}{V_2},$$

while pressure ratio is defined as the pressure increase:

$$\mathrm{PR} = \frac{P_2}{P_1}.$$

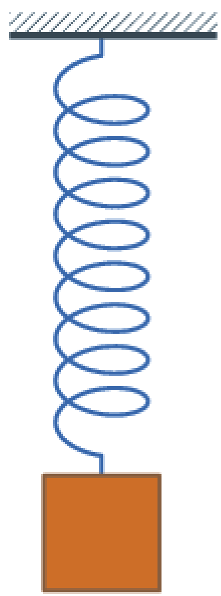
In calculating the pressure ratio, we assume that an adiabatic compression is carried out (i.e. that no heat energy is supplied to the gas being compressed, and that any temperature rise is solely due to the compression). We also assume that air is a perfect gas. With those two assumptions we can define the relationship between change of volume and change of pressure as follows:

$$P_1 V_1^\gamma = P_2 V_2^\gamma \Rightarrow \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^\gamma$$

where γ is the ratio of specific heats for air (approximately 1.4). The values in the table above are derived using this formula. Note that in reality the ratio of specific heats changes with temperature and that significant deviations from adiabatic behavior will occur.

Chapter 4

Damping Ratio



Underdamped spring-mass system with $\zeta<1$

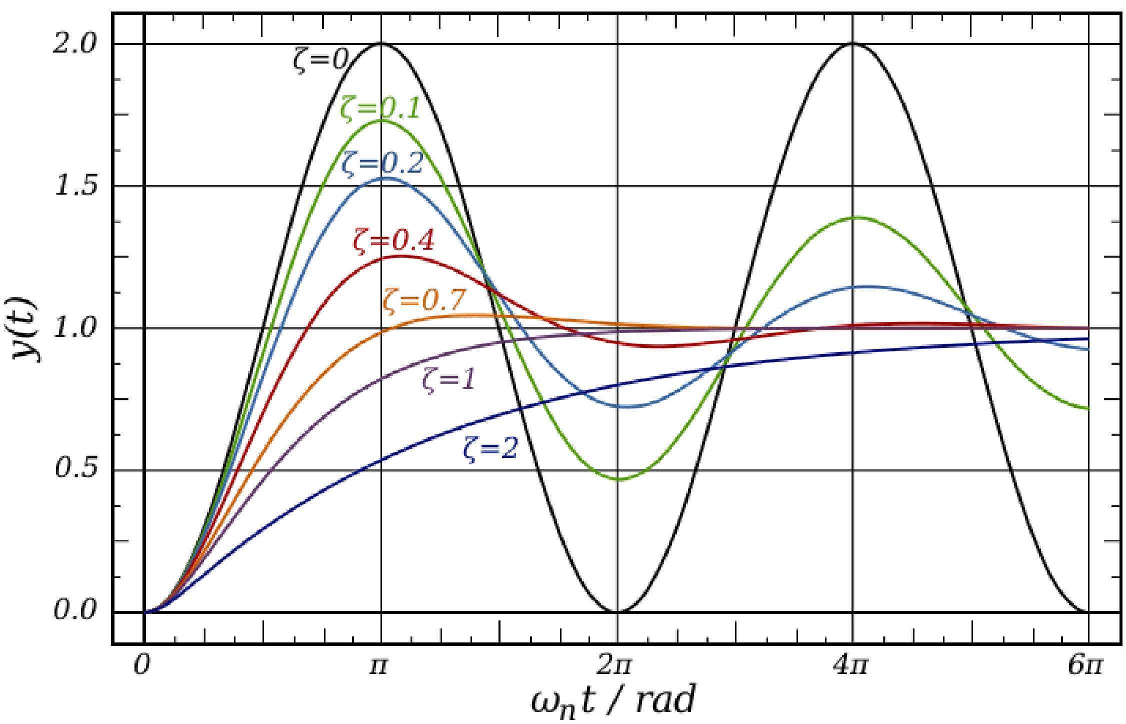
In engineering, the **damping ratio** is a dimensionless measure describing how oscillations in a system decay after a disturbance. Many systems exhibit oscillatory behavior when they are disturbed from their position of static equilibrium. A mass suspended from a spring, for example, will, if pulled and released, bounce up and down. On each bounce, the system is trying to return to its equilibrium position, but overshoots it. Frictional losses damp the system and cause the oscillations to gradually decay in amplitude towards zero. The damping ratio is a measure of describing how rapidly the oscillations decay from one bounce to the next.

The behaviour of oscillating systems is often of interest in a diverse range of disciplines that include control engineering, mechanical engineering and electrical engineering. The physical quantity that is oscillating varies greatly, and could be the swaying of a tall building in the wind, or the speed of an electric motor, but a normalised, or non-dimensionalised approach can be convenient in describing common aspects of behavior.

Oscillation modes

- Were the spring-mass system completely lossless, the mass would oscillate indefinitely, each bounce of equal height to the last. This hypothetical case is called **undamped**.
- If the system contained high losses, for example if the spring-mass experiment were conducted in a viscous fluid, the mass could slowly return to its rest position without ever overshooting. This case is called **overdamped**.
- Commonly, the mass tends to overshoot its starting position, and then return, overshooting again. With each overshoot, some energy in the system is dissipated, and the oscillations die towards zero. This case is called **underdamped**.
- Between the overdamped and underdamped cases, there exists a certain level of damping at which the system will just fail to overshoot and will not make a single oscillation. This case is called **critical damping**.

Definition



The effect of varying damping ratio on a second-order system.

The **damping ratio** is a parameter, usually denoted by ζ (zeta), that characterizes the frequency response of a second order ordinary differential equation. It is particularly important in the study of control theory. It is also important in the harmonic oscillator.

The damping ratio provides a mathematical means of expressing the level of damping in a system relative to critical damping. For a damped harmonic oscillator with mass *m*, damping coefficient *c*, and spring constant *k*, it can be defined as the ratio of the damping coefficient in the system's differential equation to the critical damping coefficient:

$$\zeta = \frac{c}{c_c}.$$

where the system differential equation is

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx = 0.$$

and the corresponding critical damping coefficient is

$$c_c = 2\sqrt{km}$$

The damping ratio is dimensionless, being the ratio of two coefficients of identical units.

The damping ratio is also related to the logarithmic decrement δ for underdamped vibrations via the relation

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} \qquad \text{where} \qquad \delta \triangleq \ln\frac{x_1}{x_2}.$$

This relation is only meaningful for underdamped systems because the logarithmic decrement is defined as the natural log of the ratio of any two successive amplitudes, and only underdamped systems exhibit oscillation.

Derivation of the damping ratio

Using the natural frequency of the simple harmonic oscillator $\omega_0 = \sqrt{k/m}$ and the definition of the damping ratio above, we can rewrite this as:

$$\frac{d^2x}{dt^2} + 2\zeta\omega_0\frac{dx}{dt} + \omega_0^2 x = 0.$$

This equation can be solved with the ansatz

$$x(t) = Ce^{st},$$

where *C* and *s* are both complex constants. That ansatz assumes a solution that is oscillatory and/or decaying exponentially. Using it in the ODE gives a condition on the frequency of the damped oscillations,

$$s = -\omega_0(\zeta \pm \sqrt{\zeta^2 - 1}).$$

- **Overdamped**:If *s* is a real number, then the solution is simply a decaying exponential with no oscillation. This case occurs for $\zeta > 1$, and is referred to as **overdamped**.

- **Underdamped**:If *s* is a complex number, then the solution is a decaying exponential combined with an oscillatory portion that looks like $\exp(i\omega_0\sqrt{1-\zeta^2})$. This case occurs for $\zeta < 1$, and is referred to as **underdamped**. (The case where $\zeta \to 0$ corresponds to the undamped simple harmonic oscillator, and in that case the solution looks like $\exp(i\omega_0)$, as expected.)

- **Critically damped**:The case where $\zeta = 1$ is the border between the overdamped and underdamped cases, and is referred to as **critically damped**. This turns out to be a desirable outcome in many cases where engineering design of a damped oscillator is required (e.g., a door closing mechanism).

Q factor and decay rate

The factors *Q*, damping ratio ζ, and exponential decay rate α are related such that

$$\zeta = \frac{1}{2Q} = \frac{\alpha}{\omega_0}.$$

When a second-order system has $\zeta < 1$ (that is, when the system is underdamped), it has two complex conjugate poles that each have a real part of α; that is, the decay rate parameter α represents the rate of exponential decay of the oscillations. A lower damping ratio implies a lower decay rate, and so very underdamped systems oscillate for long times. For example, a high quality tuning fork, which has a very low damping ratio, has an oscillation that lasts a long time, decaying very slowly after being struck by a hammer.

Chapter 5

Gear Ratio

Gears on a piece of farm equipment, total (3 gears) gear ratio 42/13 = 3.23

The **gear ratio** is the relationship between the numbers of teeth on two gears that are meshed or two sprockets connected with a common roller chain, or the circumferences of two pulleys connected with a drive belt.

General description

The input or driver gear in a gear train is the gear directly connected to the motor or other power source. Thus the driver is the gear that transmits power to the other gears in the gear train. In a simple 2-gear system, the second gear (the gear which is *turned by* the driver) is called the output or driven gear. In a gear train consisting of more than 2 gears, the final gear (the gear connected to a wheel axle or other rotating mechanical component) is the output gear.

gear ratio (gr) = (number of teeth on output or driven gear)/(number of teeth on input or driver gear)

If we assume that in the photo the smallest gear is connected to the motor, then it is the driver gear. The somewhat larger gear on the upper left is called an idler gear -- it is not connected directly to either the motor or the output shaft and serves only to transmit power between the input and output gears. There is a third gear in the upper-right corner of the photo. If we assume that gear is connected to the machine's output shaft, it is the output or driven gear.

The idler gear in this particular gear train has 21 teeth and the input gear has 13. *Considering for the moment only those two gears*, we can regard the idler as the driven gear. Therefore, the gear ratio is driven/driver = 21/13 = ~1.62 or 1.62:1.

The ratio means that the driver gear must make 1.62 revolutions to turn the driven gear 1 revolution. It also means that for every one revolution of the driver, the driven gear has made 1/1.62, or 0.62, revolutions. In practical terms, the larger gear turns more slowly.

Now suppose the third gear in the picture has 42 teeth. The gear ratio between the idler and third gear is thus 42/21, or 2:1, and hence the final gear ratio is 1.62x2=~3.23. For every 3.23 revolutions of the smallest gear, the largest gear turns one revolution, or for every one revolution of the smallest gear, the largest gear turns 0.31 (1/3.23) revolution, a total reduction of about 1:3.23 (Gear Reduction Ratio (GRR) = 1/Gear Ratio (GR)).

Since the intermediate (idler) gear contacts directly both the smaller and the larger gear it can be removed from the calculation, also giving a ratio of 42/13 = ~3.23.

Since the number of teeth is also proportional to the circumference of the gear wheel (the bigger the wheel the more teeth it has) the gear ratio can also be expressed as the relationship between the pitch circles of both wheels (where d is the pitch diameter of the input wheel and D is the pitch diameter of the output wheel):

$$gr = \frac{\pi D}{\pi d} = \frac{D}{d}$$

Pitch circles have diameters that would give the same gear ratio, but with cylindrical surfaces that do not slip.

Since the diameter is equal to twice the radius;

$$gr = \frac{D}{d} = \frac{2R}{2r} = \frac{R}{r}$$

as well.

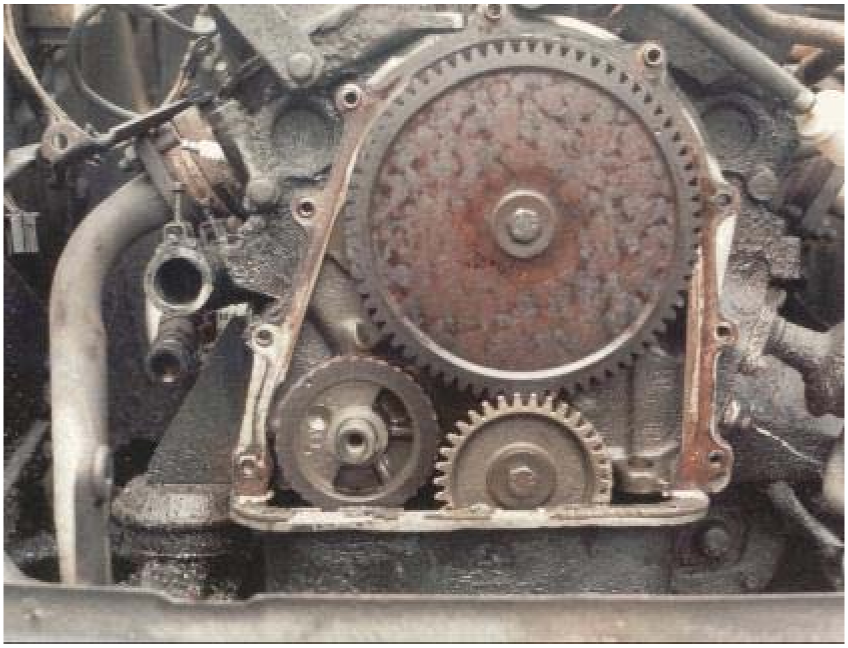
$$v_d = v_D \rightarrow \omega_d r = \omega_D R \rightarrow \frac{R}{r} = \frac{\omega_d}{\omega_D}$$

and so

$$gr = \frac{\omega_d}{\omega_D}$$

In other words, the gear ratio is proportional to ratio of the pitch circles and inversely proportional to the ratio of gear speeds.

Belts can have teeth in them also and be coupled to gear-like pulleys. Special gears called sprockets can be coupled together with chains, as on bicycles and some motorcycles. Again, exact accounting of teeth and revolutions can be applied with these machines.



Valve timing gears on a Ford Taunus V4 engine — the small gear is on the crankshaft, the larger gear is on the camshaft. The crankshaft gear has 34 teeth, the camshaft gear has 68 teeth and runs at half the crankshaft RPM.
(The small gear in the lower left is on the balance shaft.)

A belt with teeth, called the timing belt, is used in some internal combustion engines to exactly synchronize the movement of the camshaft with that of the crankshaft, so that the valves open and close at the top of each cylinder at exactly the right time relative to the movement of each piston. From the time the car is driven off the lot, to the time the belt needs replacing thousands of kilometers later, it synchronizes the two shafts exactly. A chain, called a timing chain, is used on some automobiles for this purpose, while in others, the camshaft and crankshaft are coupled directly together through meshed gears. But whichever form of drive is employed, on four-stroke engines the crankshaft/camshaft gear ratio is always 2:1, which means that for every two revolutions of the crankshaft the camshaft will rotate through one revolution.(In case of 4 stroke engines the valve cycle is repeated after every two rotations of the flywheel.)

Automobile drivetrains generally have two or more areas where gearing is used: one in the transmission, which contains a number of different sets of gearing that can be changed to allow a wide range of vehicle speeds, and another at the differential, which contains one additional set of gearing that provides further speed reduction at the wheels. As well, the differential contains further gearing that splits torque equally between the two wheels while permitting them to have different speeds when traveling a curved path. The components might be separate and connected by a driveshaft, or they might be combined into one unit called a transaxle.

A 2004 Chevrolet Corvette C5 Z06 with a six-speed manual transmission has the following gear ratios in the transmission:

Gear	Ratio
1st gear	2.97:1
2nd gear	2.07:1
3rd gear	1.43:1
4th gear	1.00:1
5th gear	0.84:1
6th gear	0.56:1
reverse	3.38:1

In 1st gear, the engine makes 2.97 revolutions for every revolution of the transmission's output. In 4th gear, the gear ratio of 1:1 means that the engine and the transmission's output are moving at the same speed. 5th and 6th gears are known as overdrive gears, in which the output of the transmission is revolving faster than the engine.

The Corvette above has a differential ratio of 3.42:1. The ratio means that for every 3.42 revolutions of the transmission's output, the wheels make one revolution. The differential ratio multiplies with the transmission ratio, so in 1st gear, the engine makes 10.16 revolutions for every revolution of the wheels.

The car's tires can almost be thought of as a third type of gearing. The example Corvette Z06 is equipped with 295/35-18 tires, which have a circumference of 82.1 inches. This means that for every complete revolution of the wheel, the car travels 82.1 inches. If the Corvette had larger tires, it would travel farther with each revolution of the wheel, which would be like a higher gear. If the car had smaller tires, it would be like a lower gear.

With the gear ratios of the transmission and differential, and the size of the tires, it becomes possible to calculate the speed of the car for a particular gear at a particular engine RPM.

For example, it is possible to determine the distance the car will travel for one revolution of the engine by dividing the circumference of the tire by the combined gear ratio of the transmission and differential.

$$d = \frac{c_t}{gr_t \times gr_d}$$

It is possible to determine a car's speed from the engine speed by multiplying the circumference of the tire by the engine speed and dividing by the combined gear ratio.

$$v_c = \frac{c_t \times v_e}{gr_t \times gr_d}$$

Gear	Distance per engine revolution	Speed per 1000 RPM
1st gear	8.1 in (210 mm)	7.7 mph (12.4 km/h)
2nd gear	11.6 in (290 mm)	11.0 mph (17.7 km/h)
3rd gear	16.8 in (430 mm)	15.9 mph (25.6 km/h)
4th gear	24.0 in (610 mm)	22.7 mph (36.5 km/h)
5th gear	28.6 in (730 mm)	27.1 mph (43.6 km/h)
6th gear	42.9 in (1,090 mm)	40.6 mph (65.3 km/h)

Wide-ratio vs. close-ratio transmission

A close-ratio transmission is a transmission in which there is a relatively little difference between the gear ratios of the gears. For example, a transmission with an engine shaft to drive shaft ratio of 4:1 in first gear and 2:1 in second gear would be considered wide-ratio when compared to another transmission with a ratio of 4:1 in first and 3:1 in second. This is because, for the wide-ratio first gear = 4/1 = 4, second gear = 2/1 = 2, so the transmission gear ratio = 4/2 = 2 (or 200%). For the close-ratio first gear = 4/1 = 4, second gear = 3/1 = 3 so the transmission gear ratio = 4/3 = 1.33 (or 133%), because 133% is less than 200%, the transmission with the 133% ratio between gears is considered close-ratio. However, not all transmissions start out with the same ratio in 1st gear or end with the same ratio in 5th gear, which makes comparing wide vs. close transmission more difficult.

Close-ratio transmissions are generally offered in sports cars, in which the engine is tuned for maximum power in a narrow range of operating speeds and the driver can be expected to enjoy shifting often to keep the engine in its power band.

Factory 4-speed or 5-speed transmission ratios are good compromises for mixed street and moderate performance use, and are "staged" or "progressive", in that the engine speed loss on shifting from 1st to 2nd is higher than the loss on shifting from 2nd to 3rd and so on. The purpose is to keep the engine in its torque range at higher vehicle speed, where wind resistance requires more power for acceleration. Wider gaps between ratios will allow a "stronger" (higher numerically, e.g. 2.90:1 instead of 2.50:1) 1st gear for better manners in traffic, but increase the RPM lost on shifting. Narrowing the gaps will increase acceleration at speed, and potentially improve top speed under certain conditions, but acceleration from stopped and operation in traffic will suffer.

The 1st gear ratio for most 4-speed transmissions is about 2.50:1, and 4th is almost always 1.00:1. The ratios of 2nd and 3rd are placed in between these two, and are discretionary to best serve the weight, intended use, speed, engine tune, and other features of the vehicle.

"Range" is the torque multiplication difference between 1st and 4th gears; wider-ratio gear-sets have more, typically between 2.8 and 3.2. This is the single most important determinant of low-speed acceleration from stopped.

"Progression" is the next factor. This is the reduction or decay in the percentage drop in engine speed in the next gear (e.g. after shifting from 1st to 2nd). Most transmissions have some degree of progression in that the RPM drop on the 1-2 shift is larger than the RPM drop on the 2-3 shift, which is in turn larger than the RPM drop on the 3-4 shift. The progression may not be linear (continuously reduced) or done in proportionate stages for various reasons, including a special need for a gear to reach a specific speed or RPM for passing, racing and so on, or simply economic necessity that the parts were available.

The two factors are not mutually exclusive, but each limits the number of options for the other. A wide range, which gives a strong torque multiplication in 1st gear for excellent manners in low-speed traffic (especially with a smaller motor, heavy chassis or numerically low axle ratio such as 2.50) mean that the progression percentages must all be high. The amount of engine speed (and therefore power) that must be lost on each up-shift is higher than would be the case in a transmission with less range (but less power in 1st gear). A numerically low 1st gear (2.00, &c.) reduces available torque in 1st gear, but allows more choices of progression.

There is no choice of ratios that gives the "best" performance at all speeds, nor is there a choice of final drive (axle) ratio that gives the "best" performance at all speeds. It simply does not exist, all ratios are compromises, and not necessarily better than the original ratios for most use.

The advantage of a close ratio gear-set lies in the fact that the RPM loss at very high speed is reduced, allowing extra power to accelerate above 100 mph. However, of necessity, the torque multiplier in the lower gears is reduced by the same proportion, and performance at low speeds is much worse. Even for road racing, the closest possible ratio is not always the best choice since many races begin with a grid start (favoring slightly wider ratios with high progression, where 1st gear acceleration is very important) and some with a flying start (favoring close ratios, where 1st gear acceleration is less important).

In general, engines with smaller displacement, very long duration cams, ported heads, large carburetors and so on don't pull well from low rpm, and when the 3-4 shift will benefit more from close ratios in the upper gears, and even more so as the maximum speed at a specific course increases. If the shift takes place at a speed where air resistance is high (70+ mph), closer ratios are better. If your engine has been specifically designed for a tuned RPM torque peak (or if that is how the engine behaves), the transmission ratios must be chosen to ensure that after each shift during a lap the engine speed recovers to a point above this peak at that specific track. From the negative viewpoint, the ratios must be arranged to avoid dropping the engine into a "hole" on an up shift, where power falls off disproportionately.

If the widest ratio change gives a 25% loss, the shift RPM is 7,000 RPM, and there is a torque increase at 5,000 RPM you're safe: 7,000 - 25% = 5,250, the engine will be in this desirable range on acceleration.

If the widest ratio change is 30%, shift at 7,000, and torque at 5,500: 7,000 - 30% = 4,900, far below the power range and the acceleration (and perhaps the jetting) will be weak until you reach 5,500. You will definitely benefit from a closer gear set, or at least re-arranging the progression to reduce the 30% drop to a better number. Depending on the bike and the track, adding to the drop in the previous gear pair (i.e., problem with the 2-3 shift: add some drop to the 1-2 not the 3-4) is the 1st choice but results will vary.

Individual race tracks with combination of maximum speed and corner speed will require different intermediate (2nd & 3rd) gears to allow downshifting for a specific gear to enter a turn, or to use only one gear during a turn to avoid traction loss. The key to analysis here is whether your favorite track has a spot where the engine is "flat" after shifting at an awkward moment in a turn, but better as it speeds up.

Idler gear

In a sequence of gears chained together, the ratio depends only on the number of teeth on the first and last gear. The intermediate gears, regardless of their size, do not alter the overall gear ratio of the chain. However, the addition of each intermediate gear reverses the direction of rotation of the final gear.

An intermediate gear which does not drive a shaft to perform any work is called an idler gear. Sometimes, a single idler gear is used to reverse the direction, in which case it may be referred to as a *reverse idler*. For instance, the typical automobile manual transmission engages reverse gear by means of inserting a reverse idler between two gears.

Idler gears can also transmit rotation among distant shafts in situations where it would be impractical to simply make the distant gears larger to bring them together. Not only do larger gears occupy more space, the mass and rotational inertia (moment of inertia) of a gear is proportional to the square of its radius. Instead of idler gears, a toothed belt or chain can be used to transmit torque over distance.

Chapter 6

Lift-to-Drag Ratio

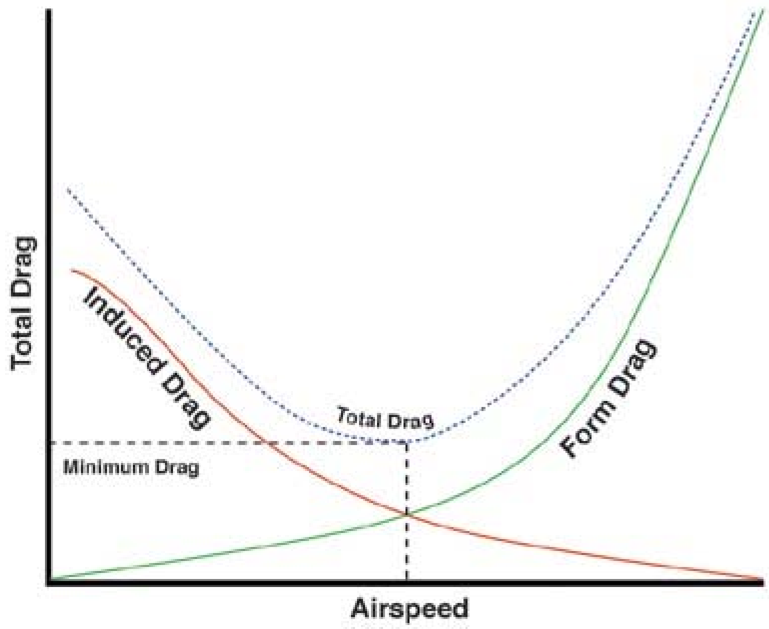
In aerodynamics, the **lift-to-drag ratio**, or **L/D ratio** ("ell-over-dee"), is the amount of lift generated by a wing or vehicle, divided by the drag it creates by moving through the air. A higher or more favorable L/D ratio is typically one of the major goals in aircraft design; since a particular aircraft's required lift is set by its weight, delivering that lift with lower drag leads directly to better fuel economy, climb performance, and glide ratio.

The term is calculated for any particular airspeed by measuring the lift generated, then dividing by the drag at that speed. These vary with speed, so the results are typically plotted on a 2D graph. In almost all cases the graph forms a U-shape, due to the two main components of drag.

Drag

Induced drag is caused by the generation of lift by the wing. Lift generated by a wing is perpendicular to the wing, but since wings typically fly at some small angle of attack, this means that a component of the force is directed to the rear. The rearward component of this force is seen as drag. At low speeds an aircraft has to generate lift with a higher angle of attack, thereby leading to greater induced drag. This term dominates the low-speed side of the L/D graph, the left side of the U.

Profile drag is caused by air hitting the wing, and other parts of the aircraft. This form of drag, also known as wind resistance, varies with the square of speed. For this reason profile drag is more pronounced at higher speeds, forming the right side of the L/D graph's U shape. Profile drag is lowered primarily by reducing cross section and streamlining.



The drag curve

The peak L/D ratio doesn't necessarily occur at the point of least total drag, as the lift produced at that speed is not high, hence a bad L/D ratio. Similarly, the speed at which the highest lift occurs does not have a good L/D ratio, as the drag produced at that speed is too high. The best L/D ratio occurs at a speed somewhere in between (usually slightly above the point of lowest drag). Designers will typically select a wing design which produces an L/D peak at the chosen cruising speed for a powered fixed-wing aircraft, thereby maximizing economy. Like all things in aeronautical engineering, the lift-to-drag ratio is not the only consideration for wing design. Performance at high angle of attack and a gentle stall are also important.

Glide ratio

As the aircraft fuselage and control surfaces will also add drag and possibly some lift, it is fair to consider the L/D of the aircraft as a whole. As it turns out, the glide ratio, which is the ratio of an (unpowered) aircraft's forward motion to its descent, is, when flown at constant speed, numerically equal to the aircraft's L/D. This is especially of interest in the design and operation of high performance sailplanes, which can have glide ratios approaching 60 to 1 (60 units of distance forward for each unit of descent) in the best cases, but with 30:1 being considered good performance for general recreational use. Achieving a glider's best L/D in practice requires precise control of airspeed and smooth and restrained operation of the controls to reduce drag from deflected control surfaces. In zero wind conditions, L/D will equal altitude lost divided by distance traveled. Achieving the maximum distance for altitude lost in wind conditions requires further modification of the best airspeed, as does alternating cruising and thermaling. To achieve high speed across country, gliders are often loaded with water ballast to increase the airspeed (allowing better penetration against a headwind). As noted below, to first order the L/D is not dependent on speed, although the faster speed means the airplane will fly at higher Reynold's number.

Theory

Mathematically, the maximum lift-to-drag ratio can be estimated as:

$$(L/D)_{max} = \frac{1}{2}\sqrt{\frac{\pi A \epsilon}{C_{D,0}}},$$

where A is the aspect ratio, ε is the aircraft's efficiency factor, and $C_{D,0}$ is the zero-lift drag coefficient.

Supersonic/hypersonic lift to drag ratios

At very high speeds, lift to drag ratios tend to be lower. Concorde had a lift/drag ratio of around 7 at Mach 2, whereas a 747 is around 17 at about mach 0.85.

Dietrich Küchemann developed an empirical relationship for predicting L/D ratio for high Mach:

$$L/D_{max} = \frac{4(M+3)}{M}$$

where M is the Mach number. Windtunnel tests have shown this to be roughly accurate.

Examples

The following table includes some representative L/D ratios.

Flight article	Scenario	L/D ratio
Virgin Atlantic GlobalFlyer	Cruise	37
Lockheed U-2	Cruise	~28
Rutan Voyager	Cruise	27
Albatross		20
Boeing 747	Cruise	17
Common tern		12
Herring gull		10
Concorde	M2 Cruise	7.14
Cessna 150	Cruise	7
Concorde	Approach	4.35
House sparrow		4

In gliding flight, the L/D ratios are equal to the glide ratio.

Flight article	Scenario	L/D ratio / Glide ratio
Modern Sailplane	gliding	45-70 (depending on span)
Hang glider		15
Gimli glider	Boeing 767-200 with fuel exhaustion	~12
Paraglider	high performance model	11
Powered parachute	Rectangular/elliptical parachute	3.6/5.6
Space Shuttle	Approach	4.5
Wingsuit	Gliding	2.5
Northern flying squirrel	Gliding	1.98
Space Shuttle	Hypersonic	1
Apollo CM	Reentry	0.368

Chapter 7

Overall Pressure Ratio

In aeronautical engineering, the term **overall pressure ratio** is defined as the ratio of the stagnation pressure as measured at the front and rear of the compressor of a gas turbine engine. Generally speaking, a higher overall pressure ratio implies higher efficiency, but the engine will weigh more, so there is an optimum.

History of overall pressure ratios

Early jet engines had limited pressure ratios due to construction innaccuracies of the compressors and various material limits. For instance, the Junkers Jumo 004 from World War II had an overall pressure ratio 3.14:1. The immediate post-war SNECMA Atar improved this marginally to 5.2:1. Improvements in materials, compressor blades, and especially the introduction of multi-spool engines with several different rotational speeds, led to the much higher pressure ratios common today. Modern civilian engines generally operate between 30 and 40:1. The three-spool Rolls-Royce Trent 900 used on the Airbus A380, for instance, has a pressure ratio of about 39:1.

Advantages of high overall pressure ratios

A high overall pressure ratio permits a larger area ratio nozzle to be fitted on the jet engine. This means that more of the heat energy is converted to jet speed, and energetic efficiency improves. This is reflected in improvements in the engine's specific fuel consumption.

Disadvantages of high overall pressure ratios

One of the primary limiting factors on pressure ratio in modern designs is that the air heats up as it is compressed. As the air travels through the compressor stages it can reach temperatures that pose a material failure risk for the compressor blades. This is especially true for the last compressor stage, and the inlet temperature to this stage, T_3, is a common figure of merit for engine designs. For civilian engines, the pressure ratio can be adjusted as the aircraft climbs, allowing it to offset some of the heat load through the lowered pressure and temperature of the high-altitude air. This is one of the many reasons airliners climb to high altitude as quickly as possible.

Military engines are often forced to work under conditions that maximize the heating load. For instance, the General Dynamics F-111 was required to operate at speeds of Mach 1.1 at sea level. As a side-effect of these wide operating conditions, and generally older technology in most cases, military engines typically have lower overall pressure ratios. The Pratt & Whitney TF30 used on the F-111 had a pressure ratio of about 20:1, while newer engines like the General Electric F110 and Pratt & Whitney F135 have improved this to about 30:1.

An additional issue is weight: a higher compression ratio implies a heavier engine, which in turn costs fuel to carry around. Thus, for a particular construction technology and set of flight plans an optimal overall pressure ratio can be determined.

Examples

Engine	Overall pressure ratio	notes
General Electric CF6	30.5:1	Boeing 747, A300
General Electric F110	30:1	F-14, F-15, F-16
Pratt & Whitney TF30	20:1	F-111
Rolls-Royce/Snecma Olympus 593	15.5:1	Concorde, Mach 2 engine

The Concorde's Olympus engines get additional compression from its supersonic inlet, yielding an effective overall pressure ratio of 80:1.

Differences from other similar terms

The term should not be confused with the more familiar term compression ratio applied to reciprocating engines. Compression ratio is a ratio of volumes. In the case of the reciprocating engine, the maximum expansion of the charge is limited by the mechanical movement of the pistons (or rotor), and so the compression can be measured by simply comparing the volume of the cylinder with the piston at the top and bottom of its motion. The same is not true of the "open ended" gas turbine, where operational and structural issues are the limiting factors. Nevertheless the two terms are similar in that they both offer a quick way of determining overall efficiency relative to other engines of the same class.

The broadly equivalent measure of rocket engine efficiency is chamber pressure/exit pressure, and this ratio can be over 2000 for the Space Shuttle Main Engine.

Compression ratio versus overall pressure ratio

For any given gas mix compression ratio and overall pressure ratio are interrelated as follows:

CR	1:1	3:1	5:1	10:1	15:1	20:1	25:1	35:1
PR	1:1	2:1	10:1	22:1	40:1	56:1	75:1	110:1

The reason for this difference is that compression ratio is defined via the volume reduction,

$$CR = \frac{V_1}{V_2},$$

Pressure ratio is defined as the pressure increase

$$PR = \frac{P_2}{P_1}.$$

From the combined gas law we get:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow \frac{V_1}{V_2} = \frac{T_1}{T_2}\frac{P_2}{P_1} \Leftrightarrow CR = \frac{T_1}{T_2}PR$$

Since T_2 is much higher than T_1 (compressing gases puts work into them, i.e. heats them up), *CR* is much lower than *PR*.

Chapter 8

Power-to-Weight Ratio

Power-to-weight ratio (or **specific power** or **power-to-mass ratio**) is a calculation commonly applied to engines and mobile power sources to enable the comparison of one unit or design to another. Power-to-weight ratio is a measurement of actual performance of any engine or power sources. It is also used as a measurement of performance of a vehicle as a whole, with the engine's power output being divided by the weight (or mass) of the vehicle, to give a metric that is independent of the vehicle's size. Power-to-weight is often quoted by manufacturers at the peak value, but the actual value may vary in use and variations will affect performance.

The inverse of power-to-weight, weight-to-power ratio (power loading) is a calculation commonly applied to aircraft, cars, and vehicles in general, to enable the comparison of one vehicle performance to another. Power-to-weight ratio is equal to powered acceleration multiplied by the velocity of any vehicle.

Power-to-weight (specific power)

The power-to-weight ratio (Specific Power) formula for an engine (power plant) is the power generated by the engine divided by weight of the engine as follows:

$$\text{P-to-W} \quad = P/W$$

A typical turbocharged V8 diesel engine might have an engine power of 330 horsepower (250 kW) and a weight of 835 pounds (379 kg), giving it a power-to-weight ratio of 0.65 kW/kg (0.40 hp/lb).

Examples of high power-to-weight ratios can often be found in turbines. This is because of their ability to operate at very high speeds. For example, the Space Shuttle's main engines use turbopumps (machines consisting of a pump driven by a turbine engine) to feed the propellants (liquid oxygen and liquid hydrogen) into the engine's combustion chamber. The original liquid hydrogen turbopump is similar in size to an automobile engine (weighing approximately 775 pounds (352 kg)) and produces 72,000 hp (53.6 MW) for a power-to-weight ratio of 153 kW/kg (93 hp/lb).

Physical interpretation

In classical mechanics, instantaneous power is the limiting value of the average rate of change of work done per unit time as the time interval Δ*t* approaches zero.

$$P = \lim_{\Delta t \to 0} \frac{\Delta W(t)}{\Delta t} = \lim_{\Delta t \to 0} P_{\text{avg}}$$

If the work to be done is rectilinear motion of a body with constant mass m, whose center of mass is to be accelerated along a straight line to a speed $|\mathbf{v}(t)|$ and angle ϕ with respect to the centre and radial of a gravitational field by an onboard powerplant, then the associated kinetic energy to be delivered to the body is equal to

$$E_K = \tfrac{1}{2} m |\mathbf{v}(t)|^2$$

where:

m is mass of the body
$|\mathbf{v}(t)|$ is speed of the center of mass of the body, changing with time.

The instantaneous mechanical pushing/pulling power delivered to the body from the powerplant is then

$$P_K = \tfrac{1}{2} m 2 |\mathbf{v}(t)| \lim_{\Delta t \to 0} \frac{\Delta |\mathbf{v}(t)|}{\Delta t} = m\mathbf{a}(t) \cdot \mathbf{v}(t) = \mathbf{F}(t) \cdot \mathbf{v}(t) = \tau(t) \cdot \omega(t)$$

where:

$\mathbf{a}(t)$ is acceleration of the center of mass of the body, changing with time.
$\mathbf{F}(t)$ is linear force - or thrust - applied upon the center of mass of the body, changing with time.
$\mathbf{v}(t)$ is velocity of the center of mass of the body, changing with time.
$\tau(t)$ is torque applied upon the center of mass of the body, changing with time.
$\omega(t)$ is angular velocity of the center of mass of the body, changing with time.

Along an obstacle free positive inclined straight road steering an automobile straight ahead, positive linear acceleration will change the speed but not the direction of the vehicle.

The weight of the body is the force applied to the body to support it at rest in a uniform gravitational field, **g**. Using Newton's Second Law of Motion, then

$$\mathbf{F_W} = -m\mathbf{g}$$

where:

m is mass of the body
$\mathbf{g}$ is gravitational field (acceleration) vector

For large changes in altitude or with a body of mass significant when compared with the gravitational field source mass, then the gravitational field may no longer be considered uniform and therefore **g** also changes with time.

The torque from the powerplant is accelerating the body to a desired velocity of motion whilst lifting the weight of the body, overcoming friction through the powerplant and upon the surface of the body (e.g. rolling resistance and skin friction), and overcoming other drag from the motion of the body through fluids (e.g. air, water). The degree in which the deliverable torque associated with the body overcomes the force of gravity upon the body and yields a net positive linear climbing acceleration, or mechanical advantage, is then

$$\mathrm{MA} = \frac{m\mathbf{a}(t) - F_F - F_D}{-m\mathbf{g}} = \frac{|\mathbf{a}(t)| - \frac{1}{m}F_F(m, |\mathbf{v}(t)|) - \frac{1}{m}F_D(|\mathbf{v}(t)|)}{|\mathbf{g}|}$$

where:

m is mass of the body
$|\mathbf{v}(t)|$ is linear speed of the center of mass of the body, changing with time.
$\mathbf{a}(t)$ is *powerplant* acceleration of the center of mass of the body, changing with time.
$\mathbf{g}$ is gravitational acceleration of the center of mass of the body.
F_F is force of friction within powerplant and upon surface of the body.
F_D is force of drag.

If the friction and drag loses are negligible, then the powerplant will convert essentially all its power to either delivering kinetic energy to the body or lifting the weight of the body. To meet this ideal, techniques include low rolling resistance tyres, sufficient tyre inflation, obstacle free path, straight asphalt road, low automotive aerodynamic drag area, well lubricated powertrain and a low loss mechanical transmission to run the engine at a speed that corresponds with the engine peak output power. The mechanical advantage is then simply

$$\text{MA} = \frac{|\mathbf{a}(t)|}{|\mathbf{g}|}$$

Power is only delivered if the powerplant is in motion, and is transmitted to cause the body to be in motion. It is typically assumed here that mechanical transmission allows the powerplant to operate at peak output power. This assumption allows engine tuning to trade power band width and engine mass for transmission complexity and mass. Electric motors do not suffer from this tradeoff. The **power advantage** or **power-to-weight ratio** is then

$$\text{P-to-W} = \frac{|\mathbf{a}(t)||\mathbf{v}(t)|}{|\mathbf{g}|}$$

where:

$|\mathbf{v}(t)|$ is linear speed of the center of mass of the body.

Power-to-weight ratio is relative to a uniform gravitational field. Normalising to any arbitrary gravitational field yields the **specific power** or **power-to-mass ratio** which is then

$$\text{P-to-M} = |\mathbf{a}(t)||\mathbf{v}(t)| = \frac{|\tau(t)||\omega(t)|}{m}$$

The power-to-weight ratio is typically calculated from power and mass, although mass is usually measured as weight on a calibrated weighing scale. Values are then expressed in units power per unit force exerted on unit mass in standard gravity. Use of kg (kilogram) and lb (pound) rather than kgf (kilogram-force), SI unit N (Newton) or lbf (pound-force) is common. The value thus expressed is the power-to-mass ratio and not the power-to-weight ratio.

The actual useful power of any traction engine can be calculated using a dynamometer to measure torque and rotational speed, with peak power sustained when transmission and/or operator keeps the product of torque and rotational speed maximised. For jet engines there is often a cruise speed and power can be usefully calculated there, for rockets there is typically no cruise speed, so it is less meaningful.

Peak power of a traction engine occurs at a rotational speed higher than the speed when torque is maximised and below the maximum rated rotational speed - Max RPM. A rapidly falling torque curve would correspond with sharp torque and power curve peaks around their maxima at similar rotational speed, for example a small, lightweight engine with a large turbocharger. A slowing falling or near flat torque curve would correspond with a slowly rising power curve up to a maximum at a rotational speed close to Max RPM, for example a large, heavy multi-cylinder engine suitable for cargo/hauling. A falling torque curve could correspond with a near flat power curve across rotational speeds for smooth handling at different vehicle speeds.

Examples

Engines

Heat engines and heat pumps

Thermal energy is made up from molecular kinetic energy and latent phase energy. Heat engines are able to convert thermal energy in the form of a temperature gradient between a hot source and a cold sink into other desirable mechanical work. Heat pumps take mechanical work to regenerate thermal energy in a temperature gradient.

Heat Engine/Heat Pump type	Peak Power Output		Power-to-weight ratio		Example Use
Wärtsilä RTA96-C 14-cylinder two-stroke Turbo Diesel engine	80,080 kW	108,920 hp	0.03 kW/kg	0.02 hp/lb	Emma Mærsk container ship
Suzuki 538 cc V2 4-stroke gas (petrol) outboard Otto engine	19 kW	25 hp	0.27 kW/kg	0.16 hp/lb	Runabout boats
DOE/NASA/0032-28 Mod 2 502 cc gas (petrol) Stirling engine	62.3 kW	83.5 hp	0.30 kW/kg	0.18 hp/lb	Chevrolet Celebrity[•] 1985
GM 6.6 L Duramax LMM (LYE option) V8 Turbo Diesel engine	246 kW	330 hp	0.65 kW/kg	0.40 hp/lb	Chevrolet Kodiak[•], GMC Topkick[•]
Junkers Jumo 205A opposed-piston two-stroke Diesel engine	647 kW	867 hp	1.1 kW/kg	0.66 hp/lb	Ju 86C-1 airliner, B&V Ha 139 floatplane
GE LM2500+ marine turboshaft Brayton gas turbine	30,200 kW	40,500 hp	1.31 kW/kg	0.80 hp/lb	GTS Millennium cruiseship, QM2 ocean liner
Mazda 13B-MSP Renesis 1.3 L Wankel engine	184 kW	247 hp	1.5 kW/kg	0.92 hp/lb	Mazda RX-8[•]
PW R-4360 71.5 L 28-cylinder supercharged Radial engine	3,210 kW	4,300 hp	1.83 kW/kg	1.11 hp/lb	B-50 Superfortress, Convair B-36 C-97 Stratofreighter, C-119 Flying Boxcar

Wright R-3350 54.57 L 18-c s/c Turbo-compound Radial engine	2,535 kW	3,400 hp	2.09 kW/kg	1.27 hp/lb	Hughes H-4 Hercules "Spruce Goose" B-29 Superfortress, Douglas DC-7 C-97 S/f prototype, Kaiser-Frazer C-119F
Pattakon OPRE two stroke Diesel engine	50 kW	70 hp	2.3 kW/kg	1.4 hp/lb	
O.S. Engines 49-PI Type II 4.97 cc UAV Wankel engine	0.934 kW	1.252 hp	2.8 kW/kg	1.7 hp/lb	Model aircraft, Radio-controlled aircraft
GE LM6000 marine turboshaft Brayton gas turbine	44,700 kW	59,900 hp	5.67 kW/kg	3.38 hp/lb	Peaking power plant
GE CF6-80C2 Brayton high-bypass turbofan jet engine					Boeing 747[•], 767, Airbus A300
BMW V10 3L P84/5 2005 gas (petrol) Otto engine	690 kW	925 hp	7.5 kW/kg	4.6 hp/lb	Williams FW27 car[•], Formula One auto racing
GE90-115B Brayton turbofan jet engine	83,164 kW	111,526 hp	10.0 kW/kg	6.10 hp/lb	Boeing 777
PWR RS-24 (SSME) Block II H_2 Brayton turbopump	63,384 kW	85,000 hp	138 kW/kg	84 hp/lb	Space Shuttle (STS-110 and later) [•]
PWR RS-24 (SSME) Block I H_2 Brayton turbopump	53,690 kW	72,000 hp	153 kW/kg	93 hp/lb	Space Shuttle

- Full vehicle power-to-weight ratio shown below

Electric motors/Electromotive generators

An electric motor uses electrical energy to provide mechanical work, usually through the interaction of a magnetic field and current-carrying conductors. By the interaction of mechanical work on an electrical conductor in a magnetic field, electrical energy can be generated.

Electric Motor type	Weight		Peak Power Output		Power-to-weight ratio		Example Use
Panasonic MSMA202S1G AC servo motor	**6.5 kg**	**14.3 lb**	**2 kW**	**2.7 hp**	**0.31 kW/kg**	**0.19 hp/lb**	**Conveyor belts, Robotics**
Toshiba 660 MVA water cooled 23kV AC turbo generator	**1,342 t**	**2,959,000 lb**	**660 MW**	**885,000 hp**	**0.49 kW/kg**	**0.30 hp/lb**	**Bayswater, Eraring Coal Power stations**
Canopy Tech. Cypress 32 MW 15 kV AC PM generator	**33,557 kg**	**73,981 lb**	**32 MW**	**42,913 hp**	**0.95 kW/kg**	**0.58 hp/lb**	**Electric Power stations**
Toyota Brushless AC NdFeB PM motor	**36.3 kg**	**80.0 lb**	**50 kW**	**67 hp**	**1.37 kW/kg**	**0.84 hp/lb**	**Toyota Prius[•] 2004**
Himax HC6332-250 Brushless DC motor	**0.45 kg**	**0.99 lb**	**1.7 kW**	**2.28 hp**	**3.78 kW/kg**	**2.30 hp/lb**	**Radio controlled cars**
Hi-Pa Drive HPD40 Brushless DC wheel hub motor	**25 kg**	**55.1 lb**	**120 kW**	**161 hp**	**4.8 kW/kg**	**2.92 hp/lb**	**Mini QED HEV, Ford F150 HEV**
ElectriFly GPMG4805 Brushless DC	**1.48 kg**	**3.26 lb**	**8.4 kW**	**11.26 hp**	**5.68 kW/kg**	**3.45 hp/lb**	**Radio-controlled aircraft**

- Full vehicle power-to-weight ratio shown below

Fluid engines and fluid pumps

Fluids (liquid and gas) can be used to transmit and/or store energy using pressure and other fluid properties. Hydraulic (liquid) and pneumatic (gas) engines convert fluid pressure into other desirable mechanical or electrical work. Fluid pumps convert mechanical or electrical work into movement or pressure changes of a fluid, or storage in a pressure vessel.

Fluid Powerplant type	Dry Weight		Peak Power Output		Power-to-weight ratio	
PlatypusPower Q2/200 hydroelectric turbine	43 kg	95 lb	2 kW	2.7 hp	0.047 kW/kg	0.029 hp/lb
PlatypusPower PP20/200 hydroelectric turbine	330 kg	728 lb	20 kW	27 hp	0.060 kW/kg	0.037 hp/lb
Atlas Copco LZL 35 pneumatic motor	20 kg	44.1 lb	5.2 kW	7 hp	0.26 kW/kg	0.16 hp/lb
Bosch 0 607 954 307 pneumatic motor	0.32 kg	0.71 lb	0.1 kW	0.13 hp	0.31 kW/kg	0.19 hp/lb
Bosch 0 607 957 307 pneumatic motor	1.7 kg	3.7 lb	0.74 kW	0.99 hp	0.44 kW/kg	0.26 hp/lb
SAI GM7 radial piston hydraulic motor	300 kg	661 lb	250 kW	335 hp	0.83 kW/kg	0.50 hp/lb
SAI GM3 radial piston hydraulic motor	15 kg	33 lb	15 kW	20 hp	1 kW/kg	0.61 hp/lb

Thermoelectric generators and electrothermal actuators

A variety of effects can be harnessed to produce thermoelectricity, thermionic emission, pyroelectricity and piezoelectricity. Electrical resistance and ferromagnetism of materials can be harnessed to generate thermoacoustic energy from an electric current.

Thermoelectric Powerplant type	Dry Weight		Peak Power Output		Power-to-weight ratio		Example Use
Teledyne Pu GPHS-RTG 1980	56 kg	123 lb	285 We	0.39 hp	5.09 W/kg	0.003 hp/lb	Galileo probe, New Horizons probe
Boeing Pu MMRTG MSL	44.1 kg	97.2 lb	123 We	0.16 hp	2.79 W/kg	0.002 hp/lb	Mars Science Laboratory

Electrochemical (galvanic) and electrostatic cell systems

(Closed cell) batteries

All electrochemical cell batteries deliver a changing voltage as their chemistry changes from "charged" to "discharged". A nominal output voltage and a cutoff voltage are typically specified for a battery by its manufacturer. The output voltage falls to the cutoff voltage when the battery becomes "discharged". The nominal output voltage is always less than the open-circuit voltage produced when the battery is "charged". The temperature of a battery can affect the power it can deliver, where lower temperatures reduce power. Total energy delivered from a single charge cycle is affected by both the battery temperature and the power it delivers. If the temperature lowers or the power demand increases, the total energy delivered at the point of "discharge" is also reduced.

Battery discharge profiles are often described in terms of a factor of battery capacity. For example a battery with a nominal capacity quoted in ampere-hours (Ah) at a C/10 rated discharge current (derived in amperes) may safely provide a higher discharge current - and therefore higher power-to-weight ratio - but only with a lower energy capacity. Power-to-weight ratio for batteries is therefore less meaningful without reference to corresponding energy-to-weight ratio and cell temperature.

Battery type	Volts	Temp.	Energy-to-weight ratio	Power-to-weight ratio
Energizer 675 Mercury Free Zinc-air battery	1.4V	21°C	1,645 kJ/kg to 0.9 V	1.65 W/kg 2.24 mA
Panasonic R03 AAA Zinc-carbon battery	1.5 V	20±2 °C	47 kJ/kg 20 mA to 0.9 V	3.3 W/kg 20 mA
			88 kJ/kg 150 mA to 0.9 V	24 W/kg 150 mA
Eagle-Picher SAR-10081 60Ah 22-cell Nickel hydrogen battery	27.7 V	10 °C	192 kJ/kg C/2 to 22 V	23 W/kg C/2
			165 kJ/kg C/1 to 22 V	46 W/kg C/1
ClaytonPower 400Ah Lithium-ion battery	12V		617 kJ/kg	85.7 W/kg C/1 (175 A)
Energizer 522 Prismatic Zn/MnO_2 Alkaline battery	9 V	21°C	444 kJ/kg 25 mA to 4.8 V	4.9 W/kg 25 mA
			340 kJ/kg 100 mA to 4.8 V	19.7 W/kg 100 mA
			221 kJ/kg 500 mA to 4.8 V	99 W/kg 500 mA
Panasonic HHR900D 9.25Ah Nickel metal hydride battery	1.2 V	20 °C	209.65 kJ/kg to 0.7 V	11.7 W/kg C/5
				58.2 W/kg C/1
				116 W/kg 2C
URI 1418Ah replaceable anode Aluminium-air battery model	244.8 V	60 °C	4680 kJ/kg	130.3 W/kg (142 A)
LG Chemical/CPI E2 6Ah $LiMn_2O_4$ Lithium-ion polymer battery	3.8 V	25 °C	530.1 kJ/kg C/2 to 3.0 V	71.25 W/kg
			513 kJ/kg 1C to 3.0 V	142.5 W/kg
Saft 45E Fe Super-Phosphate™ Lithium iron phosphate battery	3.3 V	25°C	581 kJ/kg C to 2.5 V	161 W/kg
			560 kJ/kg	183 W/kg

			1.14 C to 2.0 V	
			0.73 kJ/kg 2.27 C to 1.5 V	367 W/kg
Energizer CH35 C 1.8Ah Nickel-cadmium battery	1.2 V	21 °C	152 kJ/kg C/10 to 1 V	4 W/kg C/10
			147.1 kJ/kg 5C to 1 V	200 W/kg 5 C
Firefly Energy Oasis FF12D1-G31 6-cell 105Ah VRLA battery	12 V	25 °C	142 kJ/kg C/10 to 7.2 V	4 W/kg C/10
		-1 8°C	7 kJ/kg CCA to 7.2V	234 W/kg CCA (625A)
		0 °C	9 kJ/kg CA to 7.2 V	300 W/kg CA (800 A)
Panasonic CGA103450A 1.95Ah $LiCoO_2$ Lithium ion battery	3.7 V	20 °C	666 kJ/kg C/5.3 to 2.75 V	35 W/kg C/5.3
		0 °C	633 kJ/kg C/1 to 2.75 V	176 W/kg C/1
		20 °C	655 kJ/kg C/1 to 2.75 V	182 W/kg C/1
		20 °C	641 kJ/kg 2C to 2.75 V	356 W/kg 2C
Electric Fuel Battery Corp. UUV 120Ah Zinc-air fuel cell			630 kJ/kg	500 W/kg C/1
Sion Power 2.5Ah Li-S Lithium ion battery	2.15 V	25 °C	1260 kJ/kg	70 W/kg C/5
			1209 kJ/kg	672 W/kg 2C
Maxell / Yuasa / AIST Nickel metal hydride lab prototype		45 °C		980 W/kg
Toshiba SCiB™ cell 4.2Ah Li_2TiO_3 Lithium ion battery	2.4 V	25 °C	242 kJ/kg	67.2 W/kg C/1
			218 kJ/kg	4000 W/kg 12C
Ionix Power Systems $LiMn_2O_4$ Lithium ion battery lab model		lab	270 kJ/kg	1700 W/kg
		lab	29 kJ/kg	4900 W/kg
A123 Systems 26650 Cell 2.3Ah $LiFePO_4$ Lithium ion battery	3.3 V	-20 °C	347 kJ/kg C/1 to 2V	108 W/kg C/1
		0 °C	371 kJ/kg C/1 to 2 V	108 W/kg C/1
		25 °C	390 kJ/kg C/1 to 2 V	108 W/kg C/1
		25 °C	390 kJ/kg 27C to 2 V	3300 W/kg 27C
		25 °C	57 kJ/kg 32C to 2 V	5657 W/kg 32C

Saft VL 6Ah Lithium-ion battery	3.65 V	-20 °C	154 kJ/kg 30C to 2.5 V	41.4 W/kg 30C (180 A)
			182 kJ/kg 1C to 2.5 V	67.4 W/kg 1C
		25 °C	232 kJ/kg 1C to 2.5 V	64.4 W/kg 1C
			233 kJ/kg 58.3C to 2.5 V	3757 W/kg 58.3C (350A)
			34 kJ/kg 267C to 2.5 V	17176 W/kg 267C (1.6kA)
			4.29 kJ/kg 333C to 2.5 V	21370 W/kg 333C (2kA)

Electrostatic, electrolytic and electrochemical capacitors

Capacitors store electric charge onto two electrodes separated by an electric field semi-insulating (dielectric) medium. Electrostatic capacitors feature planar electrodes onto which electric charge accumulates. Electrolytic capacitors use a liquid electrolyte as one of the electrodes and the electric double layer effect upon the surface of the dielectric-electrolyte boundary to increase the amount of charge stored per unit volume. Electric double-layer capacitors extend both electrodes with a nanopourous material such as activated carbon to significantly increase the surface area upon which electric charge can accumulate, reducing the dielectric medium to nanopores and a very thin high permittivity separator.

Whilst capacitors tend not to be as temperature sensitive as batteries, they are significantly capacity constrained and without the strength of chemical bonds suffer from self-discharge. Power-to-weight ratio of capacitors is usually higher than batteries because charge transport units within the cell are smaller (electrons rather than ions), however energy-to-weight ratio is conversely usually lower.

Capacitor type	Capacity	Volts	Temp.	Energy-to-weight ratio	Power-to-weight ratio
ACT Premlis® Lithium ion capacitor	2000 F	4.0 V	25 °C	54 kJ/kg to 2.0 V	44.4 W/kg @ 5 A
				31 kJ/kg to 2.0 V	850 W/kg @ 10 A
Nesccap Electric double-layer capacitor	5000 F	2.7 V	25 °C	19.58 kJ/kg to 1.35 V	5.44 W/kg C/1 (1.875 A)
				5.2 kJ/kg to 1.35 V	5,200 W/kg @ 2,547A
EEStor EESU barium titanate supercapacitor	30.693 F	3500 V	85 °C	1471.98 kJ/kg	80.35 W/kg C/5
				1471.98 kJ/kg	8,035 W⁄kg 20 C

Fuel cell stacks and flow cell batteries

Fuel cells and flow cells, although perhaps using similar chemistry to batteries, have the distinction of not containing the energy storage medium or fuel. With a continuous flow of fuel and oxidant, available fuel cells and flow cells continue to convert the energy storage medium into electric energy and waste products. Fuel cells distinctly contain a fixed electrolyte whereas flow cells also require a continuous flow of electrolyte. Flow cells typically have the fuel dissolved in the electrolyte.

Fuel cell type	Dry weight	Power-to-weight ratio	Example Use
Redflow Power+BOS® ZB600 10kWh ZBB	900 kg	5.6 W/kg (9.3 W/kg peak)	Rural Grid support
Ceramic Fuel Cells BlueGen MG 2.0 CHP SOFC	200 kg	10 W/kg 15 W/kg CHP	
MTU Friedrichshafen 240 kW MCFC HotModule 2006	20 t	12 W/kg	
Smart Fuel Cell Jenny 600S 25W DMFC	1.7 kg	14.7 W/kg	Portable military electronics
UTC Power PureCell 400 kW PAFC	27,216 kg	14.7 W/kg	
GEFC 50V50A-VRB Vanadium redox battery	80 kg	31.3 W/kg (125 W/kg peak)	
Ballard Power Systems Xcellsis™ HY-205 205 kW PEMFC	2,170 kg	94.5 W/kg	Mercedes-Benz Citaro O530BZ[•]
UTC Power/NASA 12 kW AFC	122 kg	98 W/kg	Space Shuttle orbiter[•]
Ballard Power Systems FCgen-1030 1.2 kW CHP PEMFC	12 kg	100 W/kg	Residential cogeneration
Ballard Power Systems FCvelocity-HD6 150 kW PEMFC	400 kg	375 W/kg	Bus and heavy duty
Honda 2003 43 kW FC Stack PEMFC[•]	43 kg	1000 W/kg	Honda FCX Clarity[•]
Lynntech, Inc. PEMFC lab prototype	347 g	1,500 W/kg	

- Full vehicle power-to-weight ratio shown below

Photovoltaics

Photovoltaic Panel type	Power-to-weight ratio
Thyssen Solartec 128W Nanocrystalline Si Triplejunction PV module	6 W/kg
Suntech/UNSW HiPerforma PLUTO220-Udm 220W Ga-F22 Polycrystalline Si PV module	13.1 W/kg STP 9.64 W/kg

	nominal
Global Solar PN16015A 62W CIGS polycrystalline thin film PV module	40 W/kg
Able (AEC) PUMA 6 kW GaInP2/GaAs/Ge-on-Ge Triplejunction PV array	65 W/kg
Current spacecraft grade	~77 W/kg
ITO/InP on Kapton foil	2000 W/kg

Vehicles

Power-to-weight ratios for vehicles are usually calculated using curb weight (for cars) or wet weight (for motorcycles) - in other words, excluding weight of the driver and any cargo. This could be slightly misleading, especially with regard to motorcycles, where the driver might weigh 1/3 to 1/2 as much as the vehicle itself. In the sport of competitive cycling athlete's performance is increasingly being expressed in VAMs and thus as a power-to-weight ratio in W/kg. This can be measured through the use of a bicycle powermeter or calculated from measuring incline of a road climb and the rider's time to ascend it.

Utility and practical vehicles

Most vehicles are designed to meet passenger comfort and cargo carrying requirements. Different designs trade off power-to-weight ratio to increase comfort, cargo space, fuel economy, emissions control, energy security and endurance. Reduced drag and lower rolling resistance in a vehicle design can facilitate increased cargo space without increase in the (zero cargo) power-to-weight ratio. This increases the role flexibility of the vehicle. Energy security considerations can trade off power (typically decreased) and weight (typically increased), and therefore power-to-weight ratio, for fuel flexibility or drive-train hybridisation. Some utility and practical vehicle variants such as hot hatches and sports-utility vehicles reconfigure power (typically increased) and weight to provide the perception of sports car like performance or for other psychological benefit.

Notable low ratio

Vehicle	Power	Weight	Power-to-weight ratio
Benz Patent Motorwagen 954 cc 1886	560 W / 0.75 bhp	265 kg / 584 lb	2.1 W/kg / 779 lb/hp
Stephenson's Rocket 0-2-2 steam locomotive with tender 1829	15 kW / 20 bhp	4,320 kg / 9524 lb	3.5 W/kg / 476 lb/hp
CBQ Zephyr streamliner diesel locomotive with railcars 1934	492 kW / 660 bhp	94 t / 208,000 lb	5.21 W/kg / 315 lb/hp
Alberto Contador's Verbier climb 2009 Tour de France on Specialized bike	420 W / 0.56 bhp	62 kg / 137 lb	6.7 W/kg / 245 lb/hp

Force Motors Minidor Diesel 499 cc auto rickshaw	6.6 kW / 8.8 bhp	700 kg / 1543 lb	9 W/kg / 175 lb/hp
PRR Q2 4-4-6-4 steam locomotive with tender 1944	5,956 kW / 7,987 bhp	475.9 t / 1,049,100 lb	12.5 W/kg / 131 lb/hp
Mercedes-Benz Citaro O530BZ H_2 fuel cell bus 2002	205 kW / 275 bhp	14,500 kg / 32,000 lb	14.1 W/kg / 116 lb/hp
TGV BR Class 373 high-speed electric locomotive 1993	12,240 kW / 16,414 bhp	816 t / 1,798,972 lb	15 W/kg / 110 lb/hp
General Dynamics M1 Abrams Main battle tank 1980	1,119 kW / 1500 bhp	55.7 t / 122,800 lb	20.1 W/kg / 81.9 lb/hp
BR Class 43 high-speed diesel electric locomotive 1975	1,678 kW / 2,250 bhp	70.25 t / 154,875 lb	23.9 W/kg / 69 lb/hp
GE AC6000CW diesel electric locomotive 1996	4,660 kW / 6,250 bhp	192 t / 423,000 lb	24.3 W/kg / 68 lb/hp
BR Class 55 Napier Deltic diesel electric locomotive 1961	2,460 kW / 3,300 bhp	101 t / 222,667 lb	24.4 W/kg / 68 lb/hp
International CXT 2004	164 kW / 220 bhp	6,577 kg / 14500 lb	25 W/kg / 66 lb/hp
Ford Model T 2.9 L flex-fuel 1908	15 kW / 20 bhp	540 kg / 1,200 lb	28 W/kg / 60 lb/hp
TH!NK City 2008	30 kW / 40 bhp	1038 kg / 2,288 lb	28.9 W/kg / 56.9 lb/hp
Messerschmitt KR200 Kabinenroller 191 cc 1955	6 kW / 8.2 bhp	230 kg / 506 lb	30 W/kg / 50 lb/hp
Wright Flyer 1903	9 kW / 12 bhp	274 kg / 605 lb	33 W/kg / 50 lb/hp
Tata Nano 624 cc 2008	26 kW / 35 bhp	635 kg / 1,400 lb	41.0 W/kg / 40 lb/hp
Bombardier JetTrain high-speed gas turbine-electric locomotive 2000	3,750 kW / 5,029 bhp	90,750 kg / 200,000 lb	41.2 W/kg / 39.8 lb/hp
Suzuki MightyBoy 543 cc 1988	23 kW / 31 bhp	550 kg / 1,213 lb	42 W/kg / 39 lb/hp
Mitsubishi i MiEV 2009	47 kW / 63 bhp	1,080 kg / 2,381 lb	43.5 W/kg / 37.8 lb/hp
Holden FJ 2,160 cc 1953	44.7 kW / 60 bhp	1,021 kg / 2,250 lb	43.8 W/kg / 37.5 lb/hp
Chevrolet Kodiak/GMC Topkick LYE 6.6 L 2005	246 kW / 330 bhp	5126 kg / 11,300 lb	48 W/kg / 34.2 lb/hp
DOE/NASA/0032-28 Chevrolet Celebrity 502 cc ASE Mod II 1985	62.3 kW / 83.5 bhp	1,297 kg / 2,860 lb	48.0 W/kg / 34.3 lb/hp
Suzuki Alto 796 cc 2000	35 kW / 46 bhp	720 kg / 1,587 lb	49 W/kg / 35 lb/hp

Land Rover Defender 2.4 L 1990	90 kW / 121 bhp	1,837 kg / 4,050 lb	49 W/kg / 33 lb/hp

Common power

Vehicle	Power	Weight	Power-to-weight ratio
Toyota Prius 1.8 L 2010 (petrol only)	73 kW / 98 bhp	1,380 kg / 3,042 lb	53 W/kg / 31 lb/hp
Bajaj Platina Naked 100 cc 2006	6 kW / 8 bhp	113 kg / 249 lb	53 W/kg / 31 lb/hp
Subaru R2 type S 2003	47 kW / 63 bhp	830 kg / 1,830 lb	57 W/kg / 29 lb/hp
Ford Fiesta ECOnetic 1.6 L TDCi 5dr 2009	66 kW / 89 bhp	1,155 kg / 2,546 lb	57 W/kg / 29 lb/hp
Volvo C30 1.6D DRIVe S/S 3dr Hatch 2010	80 kW / 108 bhp	1,347 kg / 2,970 lb	59.4 W/kg / 27.5 lb/hp
Ford Focus ECOnetic 1.6 L TDCi 5dr Hatch 2009	81 kW / 108 bhp	1,357 kg / 2,992 lb	59.7 W/kg / 27 lb/hp
Ford Focus 1.8 L Zetec S TDCi 5dr Hatch 2009	84 kW / 113 bhp	1,370 kg / 3,020 lb	61 W/kg / 27 lb/hp
Honda FCX Clarity 4 kg Hydrogen 2008	100 kW / 134 bhp	1,600 kg / 3,528 lb	63 W/kg / 26 lb/hp
Hummer H1 6.6 L V8 2006	224 kW / 300 bhp	3,559 kg / 7,847 lb	63 W/kg / 26 lb/hp
Audi A2 1.4 L TDI 90 type S 2003	66 kW / 89 bhp	1,030 kg / 2,270 lb	64 W/kg / 25 lb/hp
Opel/Vauxhall/Holden/Chevrolet Astra 1.7 L CTDi 125 2010	92 kW / 123 bhp	1,393 kg / 3,071 lb	66 W/kg / 24.9 lb/hp
Mini (new) Cooper 1.6D 2007	81 kW / 108 bhp	1,185 kg / 2,612 lb	68 W/kg / 24 lb/hp
Toyota Prius 1.8 L 2010 (electric boost)	100 kW / 134 bhp	1,380 kg / 3,042 lb	72 W/kg / 23 lb/hp
Ford Focus 2.0 L Zetec S TDCi 5dr Hatch 2009	100 kW / 134 bhp	1,370 kg / 3,020 lb	73 W/kg / 23 lb/hp
Toyota Venza I4 2.7 L FWD 2009	136 kW / 182 bhp	1,706 kg / 3,760 lb	80 W/kg / 20.7 lb/hp
Ford Focus 2.0 L Zetec S 5dr Hatch 2009	107 kW / 143 bhp	1,327 kg / 2,926 lb	81 W/kg / 20 lb/hp
Fiat Grande Punto 1.6 L Multijet 120 2005	88 kW / 118 bhp	1,075 kg / 2,370 lb	82 W/kg / 20 lb/hp
Mini (classic) 1275GT 1969	57 kW /	686 kg /	83 W/kg /

	76 bhp	1,512 lb	20 lb/hp
Opel/Vauxhall/Holden/Chevrolet Astra 2.0 L CTDi 160 2010	118 kW / 158 bhp	1,393 kg / 3,071 lb	85 W/kg / 19.4 lb/hp
Subaru Legacy/Liberty 2.0R 2005	121 kW / 162 bhp	1,370 kg / 3,020 lb	88 W/kg / 19 lb/hp
Subaru Outback 2.5i 2008	130.5 kW / 175 bhp	1,430 kg / 3,153 lb	91 W/kg / 18 lb/hp
Smart Fortwo 1.0 L Bradbus 2009	72 kW / 97 bhp	780 kg / 1,720 lb	92 W/kg / 18 lb/hp
Ford Focus 2.0 auto 2007	104.4 kW / 140 bhp	1,198 kg / 2,641 lb	87.1 W/kg / 19 lb/hp
Toyota Venza V6 3.5 L AWD 2009	200 kW / 268 bhp	1,835 kg / 4,045 lb	109 W/kg / 15 lb/hp
Toyota Venza I4 2.7 L FWD 2009 with Lotus mass reduction	136 kW / 182 bhp	1,210 kg / 2,667 lb	112.2 W/kg / 14.7 lb/hp
Toyota Hilux V6 DOHC 4 L 4x2 Single Cab Pickup ute 2009	175 kW / 235 bhp	1,555 kg / 3,428 lb	112.5 W/kg / 14.6 lb/hp
Toyota Venza V6 3.5 L FWD 2009	200 kW / 268 bhp	1,755 kg / 3,870 lb	114 W/kg / 14.4 lb/hp

Performance luxury, roadsters and mild sports

Some utility and practical vehicles are designed for, as BMW would say, sheer driving pleasure. Increased engine performance is a consideration, but also other features associated with luxury vehicles. Longitudinal engines are common. Bodies vary from hot hatches, sedans (saloons), coupés, convertibles and roadsters. Mid-range dual-sport and cruiser motorcycles tend to have similar power-to-weight ratios.

Vehicle	Power	Weight	Power-to-weight ratio
Mini (new) Cooper 1.6T S JCW 2008	155 kW / 208 bhp	1205 kg / 2657 lb	129 W/kg / 13 lb/hp
Mazda RX-8 1.3 L Wankel 2003	173 kW / 232 bhp	1309 kg / 2888 lb	141 W/kg / 12 lb/hp
Holden Statesman/Caprice / Buick Park Avenue / Daewoo Veritas 6 L V8 2007	270 kW / 362 bhp	1891 kg / 4170 lb	143 W/kg / 12 lb/hp
Kawasaki KLR650 Gasoline DualSport 650 cc	26 kW / 35 bhp	182 kg / 401 lb	143 W/kg / 11 lb/hp
NATO HTC M1030M1 Diesel/Jet fuel DualSport 670 cc	26 kW / 35 bhp	182 kg / 401 lb	143 W/kg / 11 lb/hp
Harley-Davidson FLSTF Softail Fat Boy Cruiser 1,584 cc 2009	47 kW / 63 bhp	324 kg / 714 lb	145 W/kg / 11.3 lb/hp
BMW 7 Series 760Li 6 L V12 2006	327 kW /	2250 kg /	145 W/kg /

	439 bhp	4960 lb	11 lb/hp
Subaru Impreza WRX STi 2.0 L 2008	227 kW / 304 bhp	1530 kg / 3373 lb	148 W/kg / 11 lb/hp
Tesla Roadster 2008	185 kW / 248 bhp	1235 kg / 2723 lb	150 W/kg / 11 lb/hp
GMH HSV Clubsport / GMV VXR8 / GMC CSV CR8 / Pontiac G8 6 L V8 2006	317 kW / 425 bhp	1831 kg / 4037 lb	173 W/kg / 9.5 lb/hp

Sports vehicles and aircraft

Power-to-weight ratio is an important vehicle characteristic that affects the acceleration and handling - and therefore the driving enjoyment - of any sports vehicle. Aircraft also depend on high power-to-weight ratio to achieve sufficient lift.

Vehicle	Power	Weight	Power-to-weight ratio
Lotus Elise SC 2008	163 kW / 218 bhp	910 kg / 2006 lb	179 W/kg / 9 lb/hp
Ferrari Testarossa 1984	291 kW / 390 bhp	1506 kg / 3320 lb	193 W/kg / 9 lb/hp
Artega GT	220 kW / 300 bhp	1100 kg / 2425 lb	200 W/kg / 8 lb/hp
Lotus Exige GT3 2006	202.1 kW / 271 bhp	980 kg / 2160 lb	206 W/kg / 8 lb/hp
Bombardier Dash 8 Q400 turboprop airliner	3,781 kW / 5,071 bhp	17,185 kg / 37,888 lb	220 W/kg / 7.5 lb/hp
Chevrolet Corvette C6	321 kW / 430 bhp	1441 kg / 3177 lb	223 W/kg / 7 lb/hp
Suzuki V-Strom 650 V-twin DualSport 650 cc	50 kW / 67 bhp	194 kg / 427 lb	258 W/kg / 6.4 lb/hp
Chevrolet Corvette C6 Z06	376 kW / 505 bhp	1421 kg / 3133 lb	265 W/kg / 6 lb/hp
Porsche 911 GT2 2007	390 kW / 523 bhp	1440 kg / 3200 lb	271 W/kg / 6.1 lb/hp
Lamborghini Murciélago LP 670-4 SV 2009	493 kW / 661 bhp	1550 kg / 3417 lb	318 W/kg / 5.1 lb/hp
McLaren F1 GT 1997	467.6 kW / 627 bhp	1220 kg / 2690 lb	403 W/kg / 4 lb/hp
Supermarine Spitfire Fighter aircraft 1936	1,096 kW / 1,470 bhp	2,309 kg / 5,090 lb	475 W/kg / 3.46 lb/hp
Messerschmitt Bf 109 Fighter aircraft 1935	1,085 kW / 1,455 bhp	2,247 kg / 4,954 lb	483 W/kg / 3.40 lb/hp

Thunderbolt Land speed record car	3504 kW / 4700 bhp	7 t / 15432 lb	500 W/kg / 3.28 lb/hp
Ferrari FXX 2005	597 kW / 801 bhp	1155 kg / 2546 lb	517 W/kg / 3.2 lb/hp
Polaris Industries Assault Snowmobile 2009	115 kW / 154 bhp	221 kg / 487 lb	523 W/kg / 3.16 lb/hp
Ultima GTR 720 2006	536.9 kW / 720 bhp	920 kg / 2183 lb	583 W/kg / 3 lb/hp
Honda CBR1000RR 2009	133 kW / 178 bhp	199 kg / 439 lb	668 W/kg / 2.5 lb/hp
KillaCycle Drag racing electric motorcycle	260 kW / 350 bhp	281 kg / 619 lb	925 W/kg / 1.77 lb/hp
MTT Turbine Superbike 2008	213.3 kW / 286 bhp	227 kg / 500 lb	940 W/kg / 1.75 lb/hp
Vyrus 987 C3 4V V supercharged motorcycle 2010	157.3 kW / 211 bhp	158 kg / 348.3 lb	996 W/kg / 1.65 lb/hp
BMW Williams FW27 Formula One 2005	690 kW / 925 bhp	600 kg / 1323 lb	1150 W/kg / 1.43 lb/hp
Honda RC211V MotoGP 2004-6	176.73 kW / 237 bhp	148 kg / 326 lb	1194 W/kg / 1.37 lb/hp
Boeing 747-300 at Mach 0.84 cruise, 35,000 ft altitude	245 MW / 328,656 bhp	178.1 t / 392,800 lb	1376 W/kg / 1.20 lb/hp
John Force Racing Funny Car NHRA Drag Racing 2008	5,963.60 kW / 8,000 bhp	1043 kg / 2,300 lb	5717 W/kg / 0.30 lb/hp

Supersonic vehicles

Some sports and aerospace vehicles are capable of exceeding the speed of sound. Vehicles in this class must account for transonic wave drag, shock waves and aerodynamic heating. Turbojet, turbofan, ramjet, afterburner and rocket propulsion is common.

Vehicle	Power	Weight	Power-to-weight ratio
Space Shuttle Endeavour (OV-105)	190 MW / 255,000 bhp	78 t / 172,000 lb	2,437 W/kg / 0.7 lb/hp
Aérospatiale/BAC Concorde 1969 at Mach 2.02 supercruise full thrust	330 MW / 443,143 bhp	78.7 t / 173,500 lb	4,199 W/kg / 0.39 lb/hp
Thrust Super Sonic Car	82 MW / 110,000 bhp	10.5 t / 23,149 lb	7,812 W/kg / 0.21 lb/hp
F-35 Lightning II Multirole combat aircraft 2006 at Mach 1.67 full thrust	110 MW / 146,922 bhp	13,300 kg / 29,300 lb	8,238 W/kg / 0.20 lb/hp
Sukhoi Su-35BM Multirole combat	188.5 MW /	18,400 kg /	10,247 W/kg /

aircraft 2008 at Mach 2.25 full thrust	252,842 bhp	40,500 lb	0.16 lb/hp
Lockheed SR-71 Blackbird Surveillance aircraft 1966 at Mach 3.2, 290 kN thrust	318.3 MW / 426,853 bhp	30,600 kg / 67,461 lb	10,402 W/kg / 0.16 lb/hp
Sukhoi T-50 Stealth multirole fighter aircraft 2010 at Mach 2, 294 kN thrust	201 MW / 270,620 bhp	18,500 kg / 40,786 lb	10,908 W/kg / 0.15 lb/hp
F-22 Raptor Air superiority fighter aircraft 1990 at Mach 2.25, 312 kN thrust	241 MW / 323,088 bhp	19,700 kg / 43,430 lb	12,230 W/kg / 0.13 lb/hp
Rockwell X-30 scramjet SSTO spaceplane 1986 at Mach 30, 1.4 MN thrust (proposed)	14 GW / 19,300,000 bhp	136 t / 300,000 lb	105,740 W/kg / 0.016 lb/hp
Space Shuttle Endeavour (OV-105) with SLWT and 2 SRBs	33 GW / 44,000,000 bhp	280 t / 616,500 lb	118,000 W/kg / 0.014 lb/hp

Chapter 9

Signal-to-Noise Ratio

Signal-to-noise ratio (often abbreviated **SNR** or **S/N**) is a measure used in science and engineering to quantify how much a signal has been corrupted by noise. It is defined as the ratio of signal power to the noise power corrupting the signal. A ratio higher than 1:1 indicates more signal than noise. While SNR is commonly quoted for electrical signals, it can be applied to any form of signal (such as isotope levels in an ice core or biochemical signaling between cells).

In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of background noise. The higher the ratio, the less obtrusive the background noise is.

"Signal-to-noise ratio" is sometimes used informally to refer to the ratio of useful information to false or irrelevant data in a conversation or exchange. For example, in online discussion forums and other online communities, off-topic posts and spam are regarded as "noise" that interferes with the "signal" of appropriate discussion.

Definition

Signal-to-noise ratio is defined as the power ratio between a signal (meaningful information) and the background noise (unwanted signal):

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}},$$

where P is average power. Both signal and noise power must be measured at the same or equivalent points in a system, and within the same system bandwidth. If the signal and the noise are measured across the same impedance, then the SNR can be obtained by calculating the square of the amplitude ratio:

$$\mathrm{SNR} = \frac{P_\mathrm{signal}}{P_\mathrm{noise}} = \left(\frac{A_\mathrm{signal}}{A_\mathrm{noise}}\right)^2,$$

where *A* is root mean square (RMS) amplitude (for example, RMS voltage). Because many signals have a very wide dynamic range, SNRs are often expressed using the logarithmic decibel scale. In decibels, the SNR is defined as

$$\mathrm{SNR_{dB}} = 10\log_{10}\left(\frac{P_\mathrm{signal}}{P_\mathrm{noise}}\right) = P_\mathrm{signal,dB} - P_\mathrm{noise,dB},$$

which may equivalently be written using amplitude ratios as

$$\mathrm{SNR_{dB}} = 10\log_{10}\left(\frac{A_\mathrm{signal}}{A_\mathrm{noise}}\right)^2 = 20\log_{10}\left(\frac{A_\mathrm{signal}}{A_\mathrm{noise}}\right).$$

The concepts of signal-to-noise ratio and dynamic range are closely related. Dynamic range measures the ratio between the strongest un-distorted signal on a channel and the minimum discernable signal, which for most purposes is the noise level. SNR measures the ratio between an arbitrary signal level (not necessarily the most powerful signal possible) and noise. Measuring signal-to-noise ratios requires the selection of a representative or *reference* signal. In audio engineering, the reference signal is usually a sine wave at a standardized nominal or alignment level, such as 1 kHz at +4 dBu (1.228 V_{RMS}).

SNR is usually taken to indicate an *average* signal-to-noise ratio, as it is possible that (near) instantaneous signal-to-noise ratios will be considerably different. The concept can be understood as normalizing the noise level to 1 (0 dB) and measuring how far the signal 'stands out'.

Alternative definition

An alternative definition of SNR is as the reciprocal of the coefficient of variation, i.e., the ratio of mean to standard deviation of a signal or measurement:

$$\mathrm{SNR} = \frac{\mu}{\sigma}$$

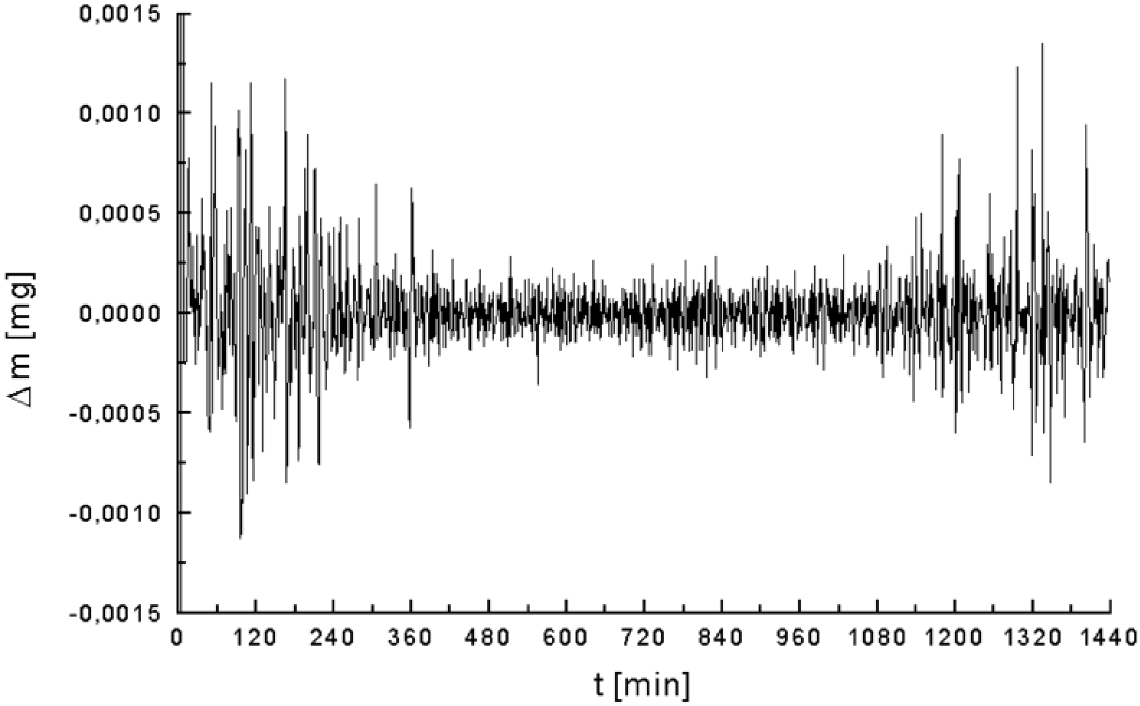
where μ is the signal mean or expected value and σ is the standard deviation of the noise, or an estimate thereof. Notice that such an alternative definition is only useful for variables that are always positive (such as photon counts and luminance). Thus it is commonly used in image processing, where the SNR of an image is usually calculated as the ratio of the mean pixel value to the standard deviation of the pixel values over a given neighborhood. Sometimes SNR is defined as the square of the alternative definition above.

The *Rose criterion* (named after Albert Rose) states that an SNR of at least 5 is needed to be able to distinguish image features at 100% certainty. An SNR less than 5 means less than 100% certainty in identifying image details.

Yet another alternative, very specific and distinct definition of SNR is employed to characterize sensitivity of imaging systems.

Related measures are the "contrast ratio" and the "contrast-to-noise ratio".

Improving SNR in practice



Recording of the noise of a thermogravimetric analysis device that is poorly isolated from a mechanical point of view; the middle of the curve shows a lower noise, due to a lesser surrounding human activity at night.

All real measurements are disturbed by noise. This includes electronic noise, but can also include external events that affect the measured phenomenon — wind, vibrations, gravitational attraction of the moon, variations of temperature, variations of humidity, etc., depending on what is measured and of the sensitivity of the device. It is often possible to reduce the noise by controlling the environment. Otherwise, when the characteristics of the noise are known and are different from the signals, it is possible to filter it or to process the signal. When the signal is constant or periodic and the noise is random, it is possible to enhance the SNR by averaging the measurement.

Digital signals

When a measurement is digitised, the number of bits used to represent the measurement determines the maximum possible signal-to-noise ratio. This is because the minimum possible noise level is the error caused by the quantization of the signal, sometimes called Quantization noise. This noise level is non-linear and signal-dependent; different calculations exist for different signal models. Quantization noise is modeled as an analog error signal summed with the signal before quantization ("additive noise").

This theoretical maximum SNR assumes a perfect input signal. If the input signal is already noisy (as is usually the case), the signal's noise may be larger than the quantization noise. Real analog-to-digital converters also have other sources of noise that further decrease the SNR compared to the theoretical maximum from the idealized quantization noise, including the intentional addition of dither.

Although noise levels in a digital system can be expressed using SNR, it is more common to use E_b/N_o, the energy per bit per noise power spectral density.

The modulation error ratio (MER) is a measure of the SNR in a digitally modulated signal.

Fixed point

For *n*-bit integers with equal distance between quantization levels (uniform quantization) the dynamic range (DR) is also determined.

Assuming a uniform distribution of input signal values, the quantization noise is a uniformly-distributed random signal with a peak-to-peak amplitude of one quantization level, making the amplitude ratio $2^n/1$. The formula is then:

$$\mathrm{DR_{dB}} = \mathrm{SNR_{dB}} = 20\log_{10}(2^n) \approx 6.02 \cdot n$$

This relationship is the origin of statements like "16-bit audio has a dynamic range of 96 dB". Each extra quantization bit increases the dynamic range by roughly 6 dB.

Assuming a full-scale sine wave signal (that is, the quantizer is designed such that it has the same minimum and maximum values as the input signal), the quantization noise approximates a sawtooth wave with peak-to-peak amplitude of one quantization level and uniform distribution. In this case, the SNR is approximately

$$\mathrm{SNR_{dB}} \approx 20\log_{10}(2^n\sqrt{3/2}) \approx 6.02 \cdot n + 1.761$$

Floating point

Floating-point numbers provide a way to trade off signal-to-noise ratio for an increase in dynamic range. For n bit floating-point numbers, with n-m bits in the mantissa and m bits in the exponent:

$$\mathrm{DR_{dB}} = 6.02 \cdot 2^m$$
$$\mathrm{SNR_{dB}} = 6.02 \cdot (n - m)$$

Note that the dynamic range is much larger than fixed-point, but at a cost of a worse signal-to-noise ratio. This makes floating-point preferable in situations where the dynamic range is large or unpredictable. Fixed-point's simpler implementations can be used with no signal quality disadvantage in systems where dynamic range is less than 6.02m. The very large dynamic range of floating-point can be a disadvantage, since it requires more forethought in designing algorithms.

Optical SNR

Optical signals have a carrier frequency, which is much higher than the modulation frequency (about 200 THz and more). This way the noise bandwidth covers a bandwidth which is much wider than the signal itself. The resulting signal influence relies mainly on the filtering of the noise. To describe the signal quality without taking the receiver into account the optical SNR (OSNR) is used. The OSNR is the ratio between the signal power and the noise power in a given bandwidth. Most commonly a reference bandwidth of 0.1 nm is used. This bandwidth is independent from the modulation format, the frequency and the receiver. For instance a OSNR of 20dB/0.1nm could be given, even the signal of 40 GBit DPSK would not fit in this bandwidth. OSNR is measured with a Optical Spectrum Analyzer

Chapter 10

Standing Wave Ratio

In telecommunications, **standing wave ratio** (**SWR**) is the ratio of the amplitude of a partial standing wave at an antinode (maximum) to the amplitude at an adjacent node (minimum), in an electrical transmission line.

The SWR is usually defined as a voltage ratio called the **VSWR**, for *voltage standing wave ratio*. For example, the VSWR value 1.2:1 denotes a maximum standing wave amplitude that is 1.2 times greater than the minimum standing wave value. It is also possible to define the SWR in terms of current, resulting in the ISWR, which has the same numerical value. The *power standing wave ratio* (PSWR) is defined as the square of the VSWR.

SWR is used as an efficiency measure for transmission lines, electrical cables that conduct radio frequency signals, used for purposes such as connecting radio transmitters and receivers with their antennas, and distributing cable television signals. A problem with transmission lines is that impedance mismatches in the cable tend to reflect the radio waves back toward the source end of the cable, preventing all the power from reaching the destination end. SWR measures the relative size of these reflections. An ideal transmission line would have an SWR of 1:1, with all the power reaching the destination and no reflected power. An infinite SWR represents complete reflection, with all the power reflected back down the cable. The SWR of a transmission line is measured with an instrument called an SWR meter, and checking the SWR is a standard part of installing and maintaining transmission lines.

Relationship to the reflection coefficient

The voltage component of a standing wave in a uniform transmission line consists of the forward wave (with amplitude V_f) superimposed on the reflected wave (with amplitude V_r).

Reflections occur as a result of discontinuities, such as an imperfection in an otherwise uniform transmission line, or when a transmission line is terminated with other than its characteristic impedance. The reflection coefficient Γ is defined thus:

$$\Gamma = \frac{V_r}{V_f}.$$

Γ is a complex number that describes both the magnitude and the phase shift of the reflection. The simplest cases, when the imaginary part of Γ is zero, are:

- Γ = − 1: maximum negative reflection, when the line is short-circuited,
- Γ = 0: no reflection, when the line is perfectly matched,
- Γ = + 1: maximum positive reflection, when the line is open-circuited.

For the calculation of VSWR, only the magnitude of Γ, denoted by ρ, is of interest. Therefore, we define

$$\rho = |\Gamma|.$$

At some points along the line the two waves interfere constructively, and the resulting amplitude $V_{\max}$ is the sum of their amplitudes:

$$V_{\max} = V_f + V_r = V_f + \rho V_f = V_f(1 + \rho).$$

At other points, the waves interfere destructively, and the resulting amplitude $V_{\min}$ is the difference between their amplitudes:

$$V_{\min} = V_f - V_r = V_f - \rho V_f = V_f(1 - \rho).$$

The voltage standing wave ratio is then equal to:

$$VSWR = \frac{V_{\max}}{V_{\min}} = \frac{1 + \rho}{1 - \rho}.$$

As ρ, the magnitude of Γ, always falls in the range [0,1], the VSWR is always ≥ +1.

The SWR can also be defined as the ratio of the maximum amplitude of the electric field strength to its minimum amplitude, i.e. $E_{\max} / E_{\min}$.

Further analysis

To understand the standing wave ratio in detail, we need to calculate the voltage (or, equivalently, the electrical field strength) at any point along the transmission line at any moment in time. We can begin with the forward wave, whose voltage as a function of time t and of distance x along the transmission line is:

$$V_f(x,t) = A\sin(\omega t - kx),$$

where A is the amplitude of the forward wave, ω is its angular frequency and k is the wave number (equal to ω divided by the speed of the wave). The voltage of the reflected wave is a similar function, but spatially reversed (the sign of x is inverted) and attenuated by the reflection coefficient ρ:

$$V_r(x,t) = \rho A\sin(\omega t + kx).$$

The total voltage V_t on the transmission line is given by the superposition principle, which is just a matter of adding the two waves:

$$V_t(x,t) = A\sin(\omega t - kx) + \rho A\sin(\omega t + kx).$$

Using standard trigonometric identities, this equation can be converted to the following form:

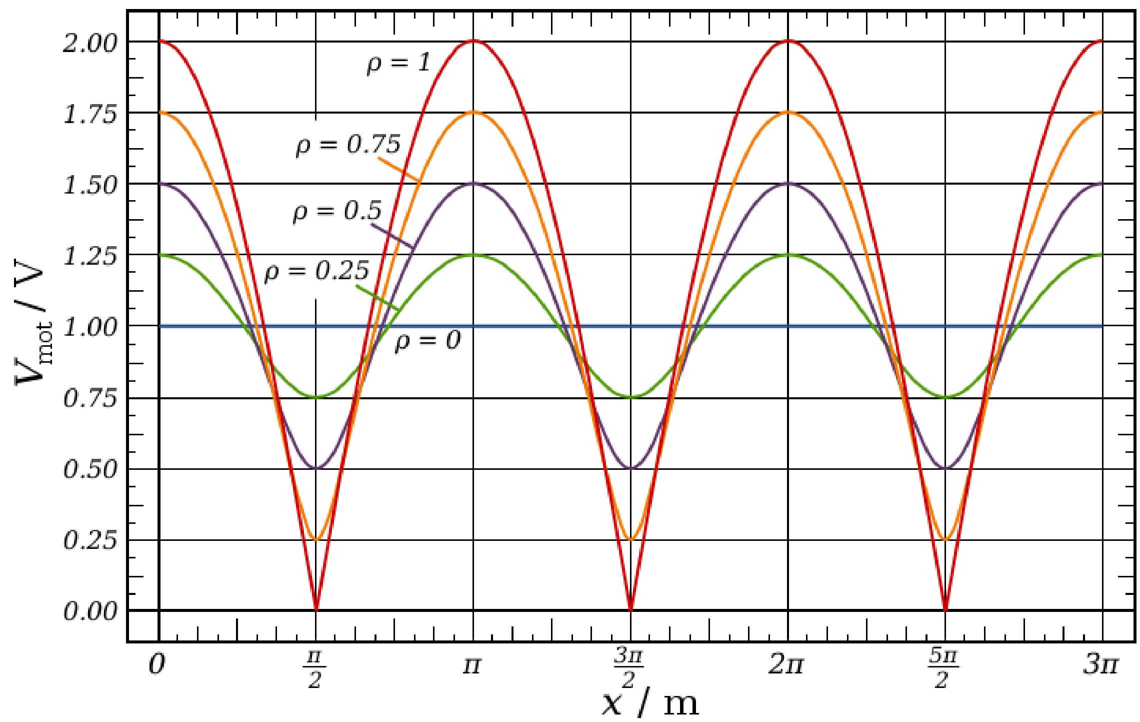
$$V_t(x,t) = A\sqrt{4\rho\cos^2 kx + (1-\rho)^2}\cos(\omega t + \phi),$$

where $$\tan\phi = \frac{(1+\rho)}{(1-\rho)}\cot(kx).$$

This form of the equation shows, if we ignore some of the details, that the maximum voltage over time V_{mot} at a distance x from the transmitter is the periodic function

$$V_{\mathbf{mot}} = A\sqrt{4\rho\cos^2 kx + (1-\rho)^2}.$$

This varies with x from a minimum of $A(1 - \rho)$ to a maximum of $A(1 + \rho)$, as we saw in the earlier, simplified discussion. A graph of V_{mot} against x, in the case when $\rho = 0.5$, is shown below. The maximum and minimum V_{mot} in a periods are V_{min} and V_{max} and are the values used to calculate the SWR.



Standing wave ratio for a range of ρ. In this graph, A and k are set to unity.

It is important to note that this graph does *not* show the instantaneous voltage profile along the transmission line. It only shows the *maximum amplitude* of the oscillation at each point. The instantaneous voltage is a function of both time and distance, so could only be shown fully by a three-dimensional or animated graph.

Practical implications of SWR

The most common case for measuring and examining SWR is when installing and tuning transmitting antennas. When a transmitter is connected to an antenna by a feed line, the impedance of the antenna and feed line must match exactly for maximum energy transfer from the feed line to the antenna to be possible. The impedance of the antenna varies based on many factors including: the antenna's natural resonance at the frequency being transmitted, the antenna's height above the ground, and the size of the conductors used to construct the antenna.

When an antenna and feedline do not have matching impedances, some of the electrical energy cannot be transferred from the feedline to the antenna. Energy not transferred to the antenna is reflected back towards the transmitter. It is the interaction of these reflected waves with forward waves which causes standing wave patterns. Reflected power has three main implications in radio transmitters: Radio Frequency (RF) energy losses increase, distortion on transmitter due to reflected power from load and damage to the transmitter can occur.

Matching the impedance of the antenna to the impedance of the feed line is typically done using an antenna tuner. The tuner can be installed between the transmitter and the feed line, or between the feed line and the antenna. Both installation methods will allow the transmitter to operate at a low SWR, however if the tuner is installed at the transmitter, the feed line between the tuner and the antenna will still operate with a high SWR, causing additional RF energy to be lost through the feedline.

Many amateur radio operators consider any impedance mismatch a serious matter. Power loss will increase as the SWR increases. For example, a dipole antenna tuned to operate at 3.75 MHz—the center of the 80 meter amateur radio band—will exhibit an SWR of about 6:1 at the edges of the band. However, if the antenna is fed with 250 feet of RG-8A coax, the loss due to standing waves is only 2.2dB, which may seem like a small loss, but is on a logarithmic scale. If running a typical 100W transmitter on the HF band, 2.2dB of loss would reduce the output power to 60W. That is a 40% reduction in power. Feed line loss typically increases with frequency, so VHF and above antennas must be matched closely to the feedline. The same 6:1 mismatch to 250 feet of RG-8A coax would incur 10.8dB of loss at 146 MHz. However, a length of 250 feet would not likely be used for 2m VHF radios. Antennas for the 80m band frequently involve large or complex designs typically mounted on a tall tower with great distances needed between buildings and thus the transmitter. VHF requires a much smaller antenna, and unless being used on a high powered repeater, does not have a very tall tower. The most common usage of 2m band is mobile single or dual band VHF or VHF/UHF mobiles. Also in part due to the typical output power of a VHF band is 50W, due to the FCC requirement of RF exposure evaluations needing to be conducted on power greater than 50W in the 2m band. This 50W with the 250 feet of cable would be reduced to a tiny 5W with 10dB of loss. On the more rare occasion where a long transmission line is needed for 146Mhz, a higher quality low loss transmission line would be used instead of the relatively cheap RG-8A.

Chapter 11

Stroke Ratio

In a reciprocating piston engine, the **stroke ratio**, defined by either **bore/stroke ratio** or **stroke/bore ratio**, is a term which is used to describe the ratio between the diameter of the cylinder bore and the length of the piston stroke within its cylinders. This can be used for either an internal combustion engine, such as a petrol- or diesel engine, where the fuel is burned within the cylinders of the engine, or external combustion engine, such as a steam engine, where the combustion of the fuel takes place *outside* the working cylinders of the engine.

While the stroke ratio can provide insight into the goals of an engine's designer, it has no direct effect on the speed at which an engine reaches maximum torque: holding displacement constant, lengthening the crank throw reduces the piston area by an exactly corresponding amount.

Conventions

In a piston engine, there are two different ways of describing the *stroke ratio* of its cylinders, and these are often mixed together causing confusion. These are: *bore/stroke* ratio, and *stroke/bore* ratio.

Bore/stroke ratio

Bore/stroke is the most commonly used term, which is mainly used in the North America, Europe, United Kingdom, Asia, Australia, and some other countries.

The diameter of the cylinder bore is divided by the length of the piston stroke to give the ratio.

Stroke/bore ratio

Stroke/bore ratio is generally more rare than **bore/stroke** ratio, but is used in some countries, like in Finland for example.

The length of the piston stroke is divided by the diameter of the cylinder bore to give the ratio.

Stroke/bore ratio is similar to the bore/stroke ratio with the following exception:

When stroke/bore value is over 1:1 the engine is long-stroke or undersquare and when the stroke/bore value is under 1:1 the engine is short-stroke or oversquare. The square engine has a value of 1:1 in both cases.

For example an engine with 110 millimetres (4.33 in) stroke and 80 millimetres (3.15 in) bore, stroke/bore value 1.375, is an undersquare or long-stroke engine. An engine that has 70 millimetres (2.76 in) stroke and 100 millimetres (3.94 in) bore, stroke/bore value 0.7, is oversquare or short-stroke.

Square, undersquare and oversquare engines

The following terms describe the naming conventions for the various configurations of the relationship ratio between the diameter of the cylinder bore and the length of the piston stroke within the cylinders of a piston engine.

Square engine

An engine is described as a **square engine** when it has equal bore *and* stroke dimensions, giving a bore/stroke value of exactly 1:1.

For example an engine which has 95 millimetres (3.74 in) bore, and an identical 95 millimetres (3.74 in) stroke, has a bore/stroke value of:

95 mm / 95 mm = 1.00

Usually engines that have a bore/stroke ratio of 0.95 to 1.04 are referred as square engines.

Square engine examples

The Volkswagen Group W16 engine as used in the Bugatti Veyron is an example of a square engine - with an identical bore and stroke of 86.0 millimetres (3.39 in). Another example of a square engine is the 1970s Ford 400M with a 4.00" bore and stroke.

The Mercedes-Benz M117 engine with a displacement of 5547 cubic centimeters is an example of a nearly square engine with a bore of 96.5 millimeters and a stroke of 94.8 millimeters.

The Cadillac 500-V8 manufactured from 1970-1976 is a nearly square engine with a 4.300 inch bore and a 4.304 inch stroke.

Nissan's SR20DE is a square engine, with a bore and stroke of 86mm.

The 1973-1976 Kawasaki Z-1 and KZ(Z)900 had a 66 mm bore and a 66 mm stroke, also making it a square engine.

Oversquare, or short-stroke engine

An engine is described as **oversquare** or **short-stroke** if its cylinders have a greater bore diameter than its stroke length - giving a ratio value of greater than 1:1.

For example an engine which has 100 millimetres (3.94 in) bore and 80 millimetres (3.15 in) stroke has a bore/stroke value of:

100 mm / 80 mm = 1.25:1

An oversquare engine allows for more and larger valves in the head of the cylinder, lower friction losses (due to the reduced distance travelled during each engine rotation) and lower crank stress (due to the lower peak piston speed relative to engine speed). Because these characteristics favor higher engine speeds, oversquare engines are often tuned to develop peak torque at a relatively high speed.

The reduced stroke length allows for a shorter cylinder and sometimes a shorter connecting rod, generally making oversquare engines less tall than undersquare engines of similar engine displacement but wider and longer (for engines with vertical cylinder axes).

By changing the crankshaft and modifying the connecting rod(s), piston(s) and/or engine block an engine can be "de-stroked". This reduces the displacement and consequently the torque of the engine, but can allow it to run at higher speeds and in fact develop greater peak power.

Oversquare engine examples

Oversquare engines are extremely common, including both Chevrolet and Ford small block V8s. Most Boxer (horizontally-opposed) engines (such as those built by Volkswagen, Porsche, and Subaru) feature oversquare designs since any increase in stroke length would result in twice the increase in overall engine size.

This is particularly crucial in Subaru's front-engine layout, where the steering angle of the front wheels is limited largely by the size of the engine. Although oversquare engines have a reputation for being high-strung, low-torque machines, the Subaru EJ engine develops peak torque at speeds as low as 3200 RPM.

Extreme examples of oversquare engine designs are found in Formula One race cars, whose rules tightly limit displacement and thereby require that power be achieved through high engine speeds. Stroke ratios of 2.5:1 are typical, with engines capable of 19,000 RPM.

Undersquare, or long-stroke engine

An engine is described as **undersquare** or **long-stroke** if its cylinders have a smaller bore (width, diameter) than its stroke (length of piston travel) - giving a ratio value of less than 1:1.

For example an engine which has 90 millimetres (3.54 in) bore and 120 millimetres (4.72 in) stroke has a bore/stroke value of:

$$90 \text{ mm} / 120 \text{ mm} = 0.75:1$$

At a given engine speed, a longer stroke increases engine friction (since the piston travels a greater distance per stroke) and increases stress on the crankshaft (due to the higher peak piston speed). The smaller bore also reduces the area available for valves in the cylinder head, requiring them to be smaller or fewer in number. Because these factors favor lower engine speeds, undersquare engines are most often tuned to develop peak torque at relatively low speeds.

An undersquare engine will typically be more compact in the directions perpendicular to piston travel but larger in the direction parallel to piston travel.

An engine can be "stroked" by replacing the crankshaft with a so-called "stroker" crankshaft and modifying the connecting rod(s), piston(s) or engine block to accommodate the increased piston travel. This increases the displacement and therefore the torque of the engine, but may reduce the peak speed at which it is safe to run.

Undersquare engine examples

Many inline engines, particularly those mounted transversely in front-wheel-drive cars, utilize an undersquare design. The smaller bore allows for a shorter engine that increases room available for the front wheels to steer. Examples of this include many Volkswagen, Honda, and Mazda engines. Some rear-wheel-drive cars that borrow engines from front-wheel-drive cars (such as the Mazda Miata) use an undersquare design.

Despite their reputation as low-speed torque machines, some undersquare engines are designed for quite high speeds. The Honda Integra Type R's B18C5 engine has one of the highest redlines of any production engine, yet features an undersquare design. The 2011 Ford Coyote engine is a modern undersquare engine with a 7,000 rpm redline.

Many British automobile companies used undersquare designs through the 1950s, largely because of a motor tax system that taxed cars by their cylinder bore. This includes the Austin A-Series engine, and many Nissan derivatives.

The Chrysler Slant-6 engine, in its most common 225 cubic inch (3.7 litre) version, is a massively undersquare engine, with a 86 millimetres (3.39 in) bore and a 105 millimetres (4.13 in) stroke, producing most of its power right on the peak of its torque curve. The Achilles heel of this engine, otherwise known for its exceptional durability, is being over-revved by inexperienced drivers. Red line for a factory engine is under 4,500 revolutions per minute (rpm); red line with aftermarket connecting rods is about 5,500 rpm. On the other hand, a well-maintained Slant-6 can be made to idle as low as 75 rpm (though this is *not* a recommended speed - neither the alternator nor the oil pump will function adequately). In some circles, the Slant-6 is nicknamed "The Stump-Puller" for its diesel engine-like low-speed torque. Appropriate gearing and driving skill is required for performance use.

Willys also used mostly undersquare engines; in fact the L134 and F134 engines, with their fairly small 79.4 millimetres (3.13 in) bore and 111.1 millimetres (4.37 in) stroke, are probably the most undersquare engines ever built (for Jeeps).

The Dodge Power Wagon, among other vehicles, used a straight-six Chrysler Flathead engine of 230 cubic inches (3.8 litre) with a bore of 83 millimetres (3.27 in) and a stroke of 117 millimetres (4.61 in), yielding a substantially under-square stroke ratio of 0.70.

Virtually all piston aircraft engines used in military aircraft were long stroke engines. The PW R-2800, Wright R-3350, PW R-4360, Rolls-Royce Merlin (1650), Allison V-1710, and Hispano-Suiza 12Y-Z are only a few of more than a hundred examples.

Chapter 12

Thrust-to-Weight Ratio

Thrust-to-weight ratio is a ratio of thrust to weight of a rocket, jet engine, propeller engine, or a vehicle propelled by such an engine. It is a dimensionless quantity and is an indicator of the performance of the engine or vehicle.

The instantaneous thrust-to-weight ratio of a vehicle varies continually during operation due to progressive consumption of fuel or propellant. The thrust-to-weight ratio based on initial thrust and weight is often published and used as a figure of merit for quantitative comparison of the initial performance of vehicles.

Calculation

The **thrust-to-weight ratio** can be calculated by dividing the thrust (in SI units – in newtons) by the weight (in newtons) of the engine or vehicle. It is a dimensionless quantity.

For valid comparison of the initial thrust-to-weight ratio of two or more engines or vehicles, thrust must be measured under controlled conditions.

Aircraft

The **thrust-to-weight ratio** and wing loading are the two most important parameters in determining the performance of an aircraft. For example, the thrust-to-weight ratio of a combat aircraft is a good indicator of the manoeuvrability of the aircraft.

The thrust-to-weight ratio varies continually during a flight. Thrust varies with throttle setting, airspeed, altitude and air temperature. Weight varies with fuel burn and changes of payload. For aircraft, the quoted thrust-to-weight ratio is often the maximum static thrust at sea-level divided by the maximum takeoff weight.

In cruising flight, the thrust-to-weight ratio of an aircraft is the inverse of the lift-to-drag ratio because thrust is equal to drag, and weight is equal to lift.

$$\left(\frac{T}{W}\right)_{cruise} = \frac{1}{\left(\frac{L}{D}\right)_{cruise}}$$

Propeller-driven aircraft

For propeller-driven aircraft, the thrust-to-weight ratio can be calculated as follows:

$$\frac{T}{W} = \left(\frac{\eta_p}{V}\right)\left(\frac{P}{W}\right)$$

where η_p is propulsive efficiency at true airspeed V

P is engine power

Rockets

The **thrust-to-weight ratio** of a rocket, or rocket-propelled vehicle, is an indicator of its acceleration expressed in multiples of gravitational acceleration g.

Rockets and rocket-propelled vehicles operate in a wide range of gravitational environments, including the *weightless* environment. It is customary to calculate the thrust-to-weight ratio using initial gross weight at sea-level on earth. This is sometimes called *Thrust-to-Earth-weight ratio*. The thrust-to-Earth-weight ratio of a rocket, or rocket-propelled vehicle, is an indicator of its acceleration expressed in multiples of earth's gravitational acceleration, g_0.

The thrust-to-weight ratio of an engine is larger for the bare engine than for the whole launch vehicle. The thrust-to-weight ratio of a bare engine is of use since it determines the maximum acceleration that any vehicle using that engine could theoretically achieve with minimum propellant and structure attached.

For a takeoff from the surface of the earth using thrust and no aerodynamic lift, the thrust-to-weight ratio for the whole vehicle has to be *more than* **one**. In general, the thrust-to-weight ratio is numerically equal to the *g-force* that the vehicle can generate. Provided the vehicle's *g-force* exceeds local gravity (expressed as a multiple of g_0) then takeoff can occur.

Many factors affect a thrust-to-weight ratio, and it typically varies over the flight with the variations of thrust due to speed and altitude, and the weight due to the remaining propellant and payload mass. The main factors that affect thrust include freestream air temperature, pressure, density, and composition. Depending on the engine or vehicle under consideration, the actual performance will often be affected by buoyancy and local gravitational field strength.

Examples

The Russian-made RD-180 rocket engine (which powers Lockheed Martin's Atlas V) produces 3,820 kN of sea-level thrust and has a dry mass of 5,307 kg. Using the Earth surface gravitational field strength of 9.807 m/s², the sea-level thrust-to-weight ratio is computed as follows: (1 kN = 1000 N = 1000 kg·m/s²)

$$\frac{T}{W} = \frac{3,820 \text{ kN}}{(5,307 \text{ kg})(9.807 \text{ m/s}^2)} = 0.07340 \ \frac{\text{kN}}{\text{N}} = 73.40 \ \frac{\text{N}}{\text{N}} = 73.40$$

Aircraft

Vehicle	T/W	Scenario
Concorde	.373	
English Electric Lightning	0.63	maximum takeoff weight, no reheat
F-15 Eagle	1.04	nominally loaded
F-16 Fighting Falcon	1.096	
Hawker Siddeley Harrier	1.1	
Dassault Rafale	1.13	
Mikoyan MiG-29	1.01	
Eurofighter Typhoon	1.25	
English Electric Lightning	~1.2	light weight, full reheat
Space Shuttle	1.5	Take-off
F-15 Eagle	~1.6	light weight, full afterburner
Space Shuttle	3	Peak (throttled back for astronaut comfort)

Note that the above duct engined aircraft do not have a thrust-to-weight ratio greater than one at maximum take-off weight, whereas rockets do.

Jet and Rocket Engines

Jet or Rocket engine	Mass, kg	Jet or rocket thrust, kN	Thrust-to-weight ratio
RD-0410 nuclear rocket engine	2000	35.2	1.8
J-58 (SR-71 Blackbird jet engine)	2722	150	5.2
Concorde's Rolls-Royce/Snecma Olympus 593 turbojet with reheat	3175	169.2	5.4
RD-0750 rocket engine, three-propellant mode	4621	1413	31.2

RD-0146 rocket engine	260	98	38.5
Space Shuttle's SSME rocket engine	3177	2278	73.2
RD-180 rocket engine	5393	4152	78.6
F-1 (Saturn V first stage)	8391	7740.5	94.1
NK-33 rocket engine	1222	1638	136.8

Fighter Aircraft

Table a: Thrust To Weight Ratios, Fuels Weights, and Weights of Different Fighter Planes

Specifications / Fighters	F-15K	F-15C	MiG-29K	MiG-29B	JF-17	J-10	F-35A	F-35B	F-35C	F-22
Engine(s) Thrust Maximum (lbf)	58,320 (2)	46,900 (2)	39,682 (2)	36,600 (2)	18,300 (1)	27,557 (1)	39,900 (1)	39,900 (1)	39,900 (1)	70,000 (2)
Aircraft Weight Empty (lb)	37,500	31,700	28,050	24,030	14,520	20,394	29,300	32,000	34,800	43,340
Aircraft Weight Full fuel (lb)	51,023	45,574	39,602	31,757	19,650	28,760	47,780	46,003	53,800	61,340
Aircraft Weight Max Take-off load (lb)	81,000	68,000	49,383	40,785	28,000	42,500	70,000	60,000	70,000	83,500
Total fuel weight (lb)	13,523	13,874	11,552	07,727	05,130	08,366	18,480	14,003	19,000	18,000
T/W ratio (Thrust / AC weight full fuel)	1.14	1.03	1.00	1.15	0.93	0.96	0.84	0.87	0.74	1.14

Table b: Thrust To Weight Ratios, Fuels Weights, and Weights of Different Fighter Planes (In International System)

In International System	F-15K	F-15C	MiG-29K	MiG-29B	JF-17	J-10	F-35A	F-35B	F-35C	F-22
Engine(s) Thrust Maximum (kgf)	26,456 (2)	21,274 (2)	18,000 (2)	16,600 (2)	08,300 (1)	12,500 (1)	18,098 (1)	18,098 (1)	18 098 (1)	31,764 (2)
Aircraft Weight Empty (kg)	17,010	14,379	12,723	10,900	06,586	09,250	13,290	14,515	15,785	19,673
Aircraft Weight Full fuel (kg)	23,143	20,671	17,963	14,405	08,886	13,044	21,672	20,867	24,403	27,836
Aircraft Weight Max Take-off load (kg)	36,741	30,845	22,400	18,500	12,700	19,277	31,752	27,216	31,752	37,869
Total fuel weight (kg)	06,133	06,292	05,240	03,505	02,300	03,794	08,382	06,352	08,618	08,163
T/W ratio (Thrust / AC weight full fuel)	1.14	1.03	1.00	1.15	0.93	0.96	0.84	0.87	0.74	1.14

- Fuel density used in calculations = 0.803 Kilograms/Liter
- The Number inside ( ) brackets is the Number of Engine(s).
- Engines powering F-15K are the Pratt & Whitney Engines, not General Electric's.
- MiG-29K's empty weight is an estimate.
- JF-17's Engine rating is of RD-93.
- JF-17 if mated with its engine WS-13, and if that engine gets its promised 18,969 lb then the T/W ratio becomes 0.97
- J-10's empty weight & fuel weight is an estimate.
- J-10's Engine rating is of AL-31FN.
- J-10 if mated with its engine WS-10A, and if that engine gets its promised 132 KN(29,674 lbf) then the T/W ratio becomes 1.03

Chapter 13

Aspect Ratio (Wing)

In aerodynamics, the **aspect ratio** of a wing is the length of the wing compared with the breadth (chord) of the wing. A high aspect ratio indicates long, narrow wings, whereas a low aspect ratio indicates short, stubby wings.

For most wings, the length of the chord varies along the wing so the aspect ratio **AR** is defined as the square of the wingspan divided by the area of the wing planform.

$$AR = \frac{b^2}{S}$$

where

b is the wingspan, and
S is the area of the wing planform.

Aspect ratio of aircraft wings

Low aspect ratio wing (AR=5.6) of a Piper PA-28 Cherokee

High aspect ratio wing (AR=12.8) of the Bombardier Dash 8 Q400

Very low aspect ratio wing (AR=1.8) of the Concorde

Very high aspect ratio wing of the Glaser-Dirks DG-808 glider(AR=27.4)

Aspect ratio and planform can be used to predict the aerodynamic performance of a wing.

For a given wing area, the aspect ratio is proportional to the square of the wingspan, and the wingspan is of particular significance in determining the performance. An airplane in flight can be imagined to affect a circular cylinder of air. The diameter of that cylinder is equal to the wingspan. A large wingspan is working on a *large* cylinder of air, and a small wingspan is working on a *small* cylinder of air. For two aircraft of the same weight but different wingspans the small cylinder of air must be pushed downward by a greater amount than the large cylinder in order to produce an equal upward force. The aft-leaning component of this change in velocity is proportional to the *induced drag*. Therefore the larger downward velocity produces a larger aft-leaning component and this leads to larger induced drag on the aircraft with the smaller wingspan and lower aspect ratio.

The interaction between undisturbed air outside the circular cylinder of air, and the downward-moving cylinder of air occurs at the wingtips, and can be seen as wingtip vortices.

This property of aspect ratio AR is illustrated in the formula used to calculate the drag coefficient of an aircraft C_d

$$C_d = C_{d0} + \frac{(C_L)^2}{\pi e AR}$$

where

C_d is the aircraft drag coefficient
C_{d0} is the aircraft zero-lift drag coefficient,
C_L is the aircraft lift coefficient,
π is the circumference-to-diameter ratio of a circle,
e is the Oswald efficiency number
AR is the aspect ratio.

There are several reasons why not *all* aircraft have high aspect wings:

- **Structural**: A long wing has higher bending stress for a given load than a short one, which requires stronger structure to withstand. Also, longer wings have greater deflection for a given load, and in some applications this deflection is undesirable (e.g. if the deflected wing interferes with aileron movement).

- **Maneuverability**: a high aspect-ratio wing will have a lower roll rate than one of low aspect ratio, because in a high-aspect-ratio wing, an equal amount of wing movement due to aileron deflection (at the aileron) will result in less rolling action on the fuselage due to the greater length between the aileron and the fuselage. A higher aspect ratio wing will also have a higher moment of inertia to overcome. Due to the lower roll rates, high aspect ratio wings are usually not used on fighter aircraft.

- **Parasitic drag**: While high aspect wings create less induced drag, they have greater parasitic drag, (drag due to shape, frontal area, and surface friction). This is because, for an equal wing *area*, the average chord (length in the direction of wind travel over the wing) is smaller. Due to the effects of Reynolds Number, the value of the section drag coefficient is an inverse logarithmic function of the characteristic length of the surface, which means that, even if two wings of the same area are flying at equal speeds and equal angles of attack, the section drag coefficient is slightly higher on the wing with the smaller chord. However, this variation is very small when compared to the variation in induced drag with changing wingspan.
  For example, the section drag coefficient c_d of a NACA 23012 airfoil (at typical lift coefficients) is inversely proportional to chord length to the power 0.129:
  $$c_d \propto \frac{1}{(\text{chord})^{0.129}}.$$
  A 20 percent increase in chord length would decrease the section drag coefficient by 2.38 percent.

- **Practicality**: low aspect ratios have a greater useful internal volume, since the maximum thickness is greater, which can be used to house the fuel tanks, retractable landing gear and other systems.

Variable aspect ratio

Extending the trailing-edge wing flaps causes a decrease in aspect ratio because extending the flaps increases the wing chord but with no change in wingspan. This decrease in aspect ratio causes an increase in induced drag which is detrimental to the airplane's performance during takeoff but may be beneficial during landing.

Aircraft which approach or exceed the speed of sound sometimes incorporate variable-sweep wings. This is due to the difference in fluid behavior in the subsonic and transonic/supersonic regimes. In subsonic flow, induced drag is a significant component of total drag, particularly at high angle of attack. However, as the flow becomes transonic and then supersonic, the shock wave first generated along the wing's upper surface causes wave drag on the aircraft, and this drag is proportional to the length of the wing - the longer the wing, the longer the shock wave. Thus a long wing, valuable at low speeds, becomes a detriment at transonic speeds. If the aircraft design can fulfil its mission profiles with the extra weight and complexity of a moveable wing, the swing-wing provides a solution to this problem.

Aspect ratio of bird wings

High aspect ratio wings abound in nature. Most birds that fly long distances have wings of high aspect ratio, and with tapered or elliptical wingtips. This is particularly noticeable on soaring birds such as albatrosses and eagles. By contrast, hawks of the genus *Accipiter* such as the Eurasian Sparrowhawk have wings of low aspect ratio (and long tails) for maneuverability.

Chapter 14

Carrier-to-Noise Ratio and Gliding Flight

Carrier-to-noise ratio

In telecommunications, the **carrier-to-noise ratio**, often written CNR or *C/N*, is the signal-to-noise ratio (SNR) of a modulated signal. The term is used to distinguish the CNR of the radio frequency passband signal from the SNR of an analogue base band message signal after demodulation, for example an audio frequency analogue message signal. If this distinction is not necessary, the term SNR is often used instead of CNR, with the same definition.

Digitally modulated signals (e.g. QAM or PSK) are basically made of two CW carriers (the I and Q components, which are out-of-phase carriers) . In fact, the information (bits or symbols) is carried by given combinations of phase and/or amplitude of the I and Q components. It is for this reason that, in the context of digital modulations, digitally modulated signals are usually referred to as carriers. Therefore, the term carrier-to-noise-ratio (CNR), instead of signal-to-noise-ratio (SNR) is preferred to express the signal quality when the signal has been digitally modulated.

High *C/N* ratios provide good quality of reception, for example low bit error rate (BER) of a digital message signal, or high SNR of an analogue message signal.

Definition

The carrier-to-noise ratio is defined as the ratio of the received modulated carrier signal power *C* to the received noise power *N* after the receive filters:

$$\mathrm{CNR} = \frac{C}{N}.$$

When both carrier and noise are measured across the same impedance, this ratio can equivalently be given as:

$$\mathrm{CNR} = \left(\frac{V_C}{V_N}\right)^2,$$

where V_C and V_N are the root mean square (RMS) voltage levels of the carrier signal and noise respectively.

C/N ratios are often specified in decibels (dB):

$$\mathrm{CNR_{dB}} = 10\log_{10}\left(\frac{C}{N}\right) = C_{dB} - N_{dB}$$

or in term of voltage:

$$\mathrm{CNR_{dB}} = 10\log_{10}\left(\frac{V_C}{V_N}\right)^2 = 20\log_{10}\left(\frac{V_C}{V_N}\right)$$

The *C/N* ratio is measured in a manner similar to the way the signal-to-noise ratio (*S/N*) is measured, and both specifications give an indication of the quality of a communications channel.

In the famous Shannon–Hartley theorem, the *C/N* ratio is equivalently to the *S/N* ratio. The *C/N* ratio resembles the carrier-to-interference ratio (*C/I*, **CIR**), and the carrier-to-noise-and-interference ratio, *C/(N+I)* or **CNIR**.

Gliding flight

Gliding flight is heavier-than-air flight without the use of thrust. It is employed by gliding animals and by aircraft such as gliders. The most common human application of gliding flight is in sport and recreation using aircraft designed for this purpose. However almost all powered aircraft are capable of gliding without engine power.

Instances of gliding flight

Aircraft ("gliders")

Most winged aircraft can glide to some extent, but there are several types of aircraft designed to glide:

- Gliders, also known as sailplanes
- Hang gliders

- Paragliders and ram-air parachutes
- Rotor kites, if untethered, these are rotary gliders. Also known as gyrogliders.
- Military gliders
- Paper aeroplane
- Radio-controlled glider
- Rocket gliders

The main human application is currently recreational, though during the Second World War military gliders were used for carrying troops and equipment into battle. The types of aircraft that are used for sport and recreation are classified as gliders (sailplanes), hang gliders and paragliders. These two latter types are often foot-launched. The design of all three types enables them to repeatedly climb using rising air and then to glide before finding the next source of lift. When done in gliders (sailplanes), the sport is known as gliding and sometimes as soaring. For foot-launched aircraft, it is known as hang gliding and paragliding. Radio-controlled gliders with fixed wings are also soared by enthusiasts.

In addition to motor gliders, some powered aircraft are designed for routine glides during part of their flight; usually when landing after a period of a powered flight. These include:

- Experimental aircraft such as the North American X-15, which glided back having used their fuel
- Spacecraft such as the Space Shuttles, SpaceShipOne and the Russian Buran

Some aircraft are not primarily designed to glide except in an emergency, for example airliners that have run out of fuel like the Gimli glider.

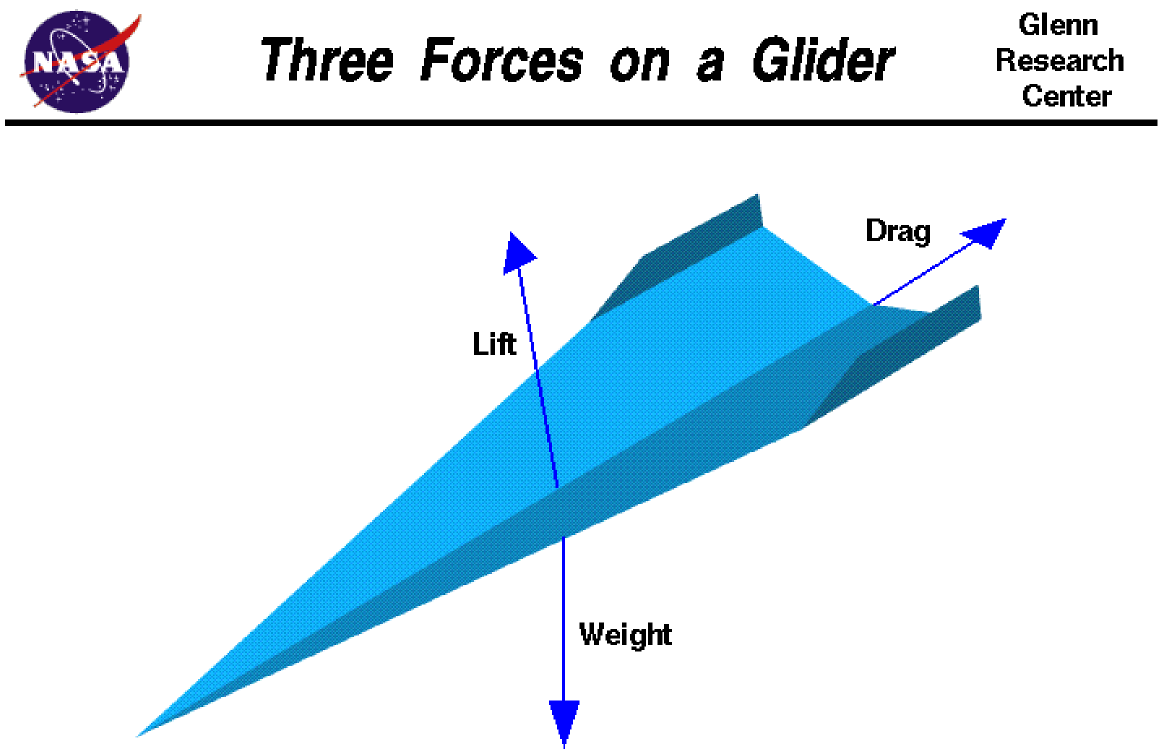
Animals

A number of animals have separately evolved gliding many times, without any single ancestor. Birds in particular use gliding flight to minimise their use of energy. Large birds are notably adept at gliding, including:

- Albatross
- Condor
- Vulture
- Eagles
- Storks

Like recreational aircraft, they too can alternate periods of gliding with periods of soaring in rising air, and so spend a considerable time airborne with a minimal expenditure of energy. For similar reasons to birds, bats can glide efficiently.

Other mammals such as gliding possums and flying squirrels also glide, but with much poorer efficiency than birds and cannot gain height. For these creatures, gliding has mainly evolved to get from tree to tree in rainforests, most especially Borneo, where the trees are tall and widely spaced. This mode of flight involves flying a greater distance horizontally than vertically and is therefore can be distinguished from a simple descent like a parachute. Some reptiles, amphibians and flying fish also glide.



Forces on a gliding animal or aircraft in flight

Forces in gliding flight

Three principle forces act on aircraft and animals when gliding:

- weight - gravity acts in the downwards direction
- lift - acts perpendicularly to the vector representing airspeed
- drag - acts parallel to the vector representing the airspeed

As the aircraft or animal descends, the air moving over the wings generates lift. The lift force acts slightly forward of vertical because it is created at right angles to the airflow which comes from slightly below as the glider descends, see Angle of attack. This horizontal component of lift is enough to overcome drag and allows the glider to accelerate forward. Even though the weight causes the aircraft to descend, if the air is rising faster than the sink rate, there will be gain of altitude.

Lift to drag ratio

The lift-to-drag ratio, or **L/D ratio** ("ell-over-dee" in the US, "ell-dee" in the UK), is the amount of lift generated by a wing or vehicle, divided by the drag it creates by moving through the air. A higher or more favourable L/D ratio is typically one of the major goals in aircraft design; since a particular aircraft's needed lift is set by its weight, delivering that lift with lower drag leads directly to better fuel economy and climb performance.

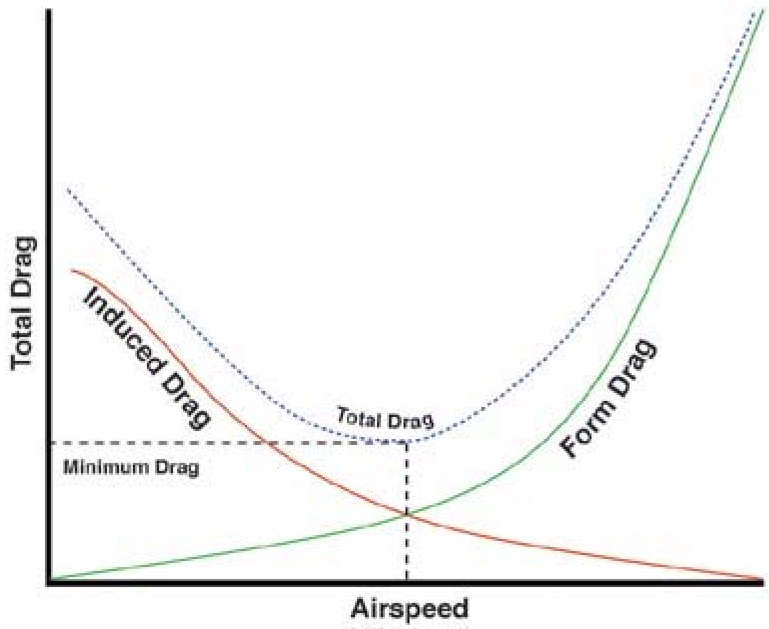
The term is calculated for any particular airspeed by dividing the measured lift by the measured drag at that speed. When measured against speed, the results can be plotted on a 2D graph. The lift curve proceeds in a straight line towards the critical angle, where it sharply drops off, and the drag curve forms a parabolic or U shape, the symmetry and shape depending on the effect of two main components of drag. The L/D curve normally forms a lopsided upside down U shape which peaks around the point of minimum drag.

As lift and drag are both proportional to the coefficient or Lift and Drag respectively multiplied by the same factor ($1/2mv^2S$), the L/D ratio can be simplified to the Coefficient of lift divided by the coefficient of drag or Cl/Cd, and since both are proportional to the airspeed, the ratio of L/D or Cl/Cd is then typically plotted against angle of attack.

Drag

Induced drag is caused by the generation of lift by the wing. Lift generated by a wing is perpendicular to the wing, but since wings typically fly at some small angle of attack, this means that a component of the force is directed to the rear. The rearward component of this force is seen as drag. At low speeds an aircraft has to generate lift with a higher angle of attack, thereby leading to greater induced drag. This term dominates the low-speed side of the drag graph, the left side of the U.

Profile drag is caused by air hitting the wing, and other parts of the aircraft. This form of drag, also known as wind resistance, varies with the square of speed. For this reason profile drag is more pronounced at higher speeds, forming the right side of the drag graph's U shape. Profile drag is lowered primarily by reducing cross section and streamlining.



The drag curve

As lift increases steadily until the critical angle, it is normally the point where the combined drag is at its lowest, that the wing or aircraft is performing at its best L/D.

Designers will typically select a wing design which produces an L/D peak at the chosen cruising speed for a powered fixed-wing aircraft, thereby maximizing economy. Like all things in aeronautical engineering, the lift-to-drag ratio is not the only consideration for wing design. Performance at high angle of attack and a gentle stall are also important.

Minimising drag is of particular interest in the design and operation of high performance glider (sailplane)s, the largest of which can have glide ratios approaching 60 to 1, though many others have a lower performance; 25:1 being considered adequate for training use.

Glide ratio

When flown at a constant speed in still air a glider moves forwards a certain distance for a certain distance downwards. The ratio of the distance forwards to downwards is called the *glide ratio*. The glide ratio is numerically equal to the Lift-to-drag ratio under these conditions; but is not necessarily equal during other manoeuvres, especially if speed is not constant. A glider's glide ratio varies with airspeed, but there is a maximum value which is frequently quoted. Glide ratio usually varies little with vehicle loading however, a heavier vehicle glides faster, but maintains its glide ratio.

Glide ratio is also known as glide number, finesse and is the cotangent of the downward angle- the **glide angle**. Alternatively it is also the forward speed divided by sink speed (unpowered aircraft):

$$\frac{L}{D} = \frac{\Delta s}{\Delta h} = \frac{v_{\text{forward}}}{v_{\text{down}}}$$

Examples

Flight article	Scenario	L/D ratio / Glide ratio
Modern Sailplane	gliding	45-70 (depending on span)
Hang glider		15
Gimli glider	Boeing 767-200 with fuel exhaustion	~12
Paraglider	high performance model	11
Powered parachute	Rectangular/elliptical parachute	3.6/5.6
Space Shuttle	Approach	4.5
Wingsuit	Gliding	2.5
Northern flying squirrel	Gliding	1.98
Space Shuttle	Hypersonic	1
Apollo CM	Reentry	0.368

Importance of the glide ratio in gliding flight

Although the best glide ratio is important when measuring the performance of a gliding aircraft, its glide ratio at a range of speeds also determines its success.

Pilots sometimes fly at the aircraft's best L/D by precisely controlling of airspeed and smoothly operating the controls to reduce drag. However the strength of the likely next lift and the strength of the wind also affects the optimal speed to fly. To achieve higher speed across country, glider (sailplanes) are often loaded with water ballast to increase the airspeed and so reach the next area of lift sooner. This has little effect on the glide angle but increases the rate of sink because the aircraft is flying at a higher speed.

If the air is rising faster than the rate of sink, the aircraft will climb. At lower speeds an aircraft may have a worse glide ratio but it will also have a lower rate of sink. A low airspeed also improves its ability to turn tightly in centre of the rising air where the rate of ascent is greatest. A sink rate of approximately 1.0 m/s is the most that a practical hang glider or paraglider could have before it would limit the occasions that a climb was possible to only when there was strongly rising air. Gliders (sailplanes) have minimum sink rates of between 0.4 and 0.6 m/s depending on the class. Aircraft such as airliners may have a better glide ratio than a hang glider, but would rarely be able to thermal because of their much higher forward speed and their much higher sink rate. (Note that the Boeing 767 in the Gimli Glider incident achieved a glide ratio of only 12:1.)

During landing, a high lift/drag ratio is desirable. Some aircraft therefore employ flaps, to increase their performance at lower speeds. Experiments with lifting bodies show that a lift/drag ratio below about 2 makes landing very difficult because of the high rate of descent.

The loss of height can be measured at several speeds and plotted on a "polar curve" to calculate the best speed to fly in various conditions, such as when flying into wind or when in sinking air. Other polar curves can be measured by loading the glider with water ballast. When ballast is carried, the best glide ratio is achieved at higher speeds (the glide ratio is not increased).

Soaring

Soaring animals and aircraft may alternate glides with periods of soaring in rising air. Five principal types of lift are used: thermals, ridge lift, lee waves, convergences and dynamic soaring. Dynamic soaring is used predominately by birds, and some model aircraft, though it has also been achieved on rare occasions by piloted aircraft.

Examples of soaring flight by birds are the use of:

- Thermals and convergences by raptors such as vultures
- Ridge lift by gulls near cliffs
- Wave lift by migrating birds
- Dynamic effects near the surface of the sea by albatrosses

For humans, soaring is the basis for three air sports: gliding, hang gliding and paragliding.

Chapter 15

Signal-to-Quantization-Noise Ratio, Steering Ratio and Eb/N0

Signal-to-quantization-noise ratio

Signal-to-Quantization-Noise Ratio (**SQNR** or **SN$_q$R**) is widely used quality measure in analysing digitizing schemes such as PCM (pulse code modulation) and multimedia codecs. The SQNR reflects the relationship between the maximum nominal signal strength and the quantization error (also known as quantization noise) introduced in the analog-to-digital conversion.

The SQNR formula is derived from the general SNR (Signal-to-Noise Ratio) formula for the binary pulse-code modulated communication channel:

$$\mathrm{SNR} = \frac{3 \times 2^{2n}}{1 + 4P_e \times (2^{2n} - 1)} \frac{\overline{m(t)}^2}{m(t)^2}$$

where

P_e is the probability of received bit error
$\underline{m(t)}$ is the peak message signal level
$m(t)$ is the mean message signal level

As SQNR applies to quantized signals, the formulae for SQNR refer to discrete-time digital signals. Instead of $m(t)$, we will use the digitized signal $x(n)$. For N quantization steps, each sample, x requires $\nu = \log_2 N$ bits. The probability distribution function (pdf) representing the distribution of values in x and can be denoted as $f(x)$. The maximum magnitude value of any x is denoted by x_{max}.

As SQNR, like SNR, is a ratio of signal power to some noise power, it can be calculated as:

$$\mathrm{SQNR} = \frac{P_{signal}}{P_{noise}} = \frac{E[x^2]}{E[\tilde{x}^2]}$$

The signal power is:

$$\overline{x^2} = E[x^2] = P_{x^\nu} = \int x^2 f(x)dx$$

The quantization noise power can be expressed as:

$$E[\tilde{x}^2] = \frac{x_{max}^2}{3 \times 4^\nu}$$

Giving:

$$\mathrm{SQNR} = \frac{3 \times 4^\nu \overline{x^2}}{x_{max}^2}$$

When the SQNR is desired in terms of Decibels (dB), a useful approximation to SQNR is:

$$\mathrm{SQNR}|_{dB} = P_{x^\nu} + 6\nu + 4.8$$

where ν is the number of bits in a quantized sample, and P_{x^ν} is the signal power calculated above. Note that for each bit added to a sample, the SQNR goes up by approximately 6dB ($20 \times log_{10}(2)$).

Steering ratio

Steering ratio refers to the ratio between the turn of the steering wheel (in degrees) or handlebars and the turn of the wheels (in degrees).

The steering ratio, is the amount of degrees you have to turn the steering wheel, for the wheels to turn an amount of degrees. In motorcycles and bicycles, the steering ratio is always 1:1, because the steering wheel will always follow the wheel. x:y means that you have turn the steering wheel x degree(s), for the wheel(s) to turn y degree(s). In most passenger cars, the ratio is between 12:1 and 20:1. **Example:** If one complete turn of the steering wheel, 360 degrees, causes the wheels to turn 24 degrees, the ratio is then 360:24 = 15:1 (360/24=15).

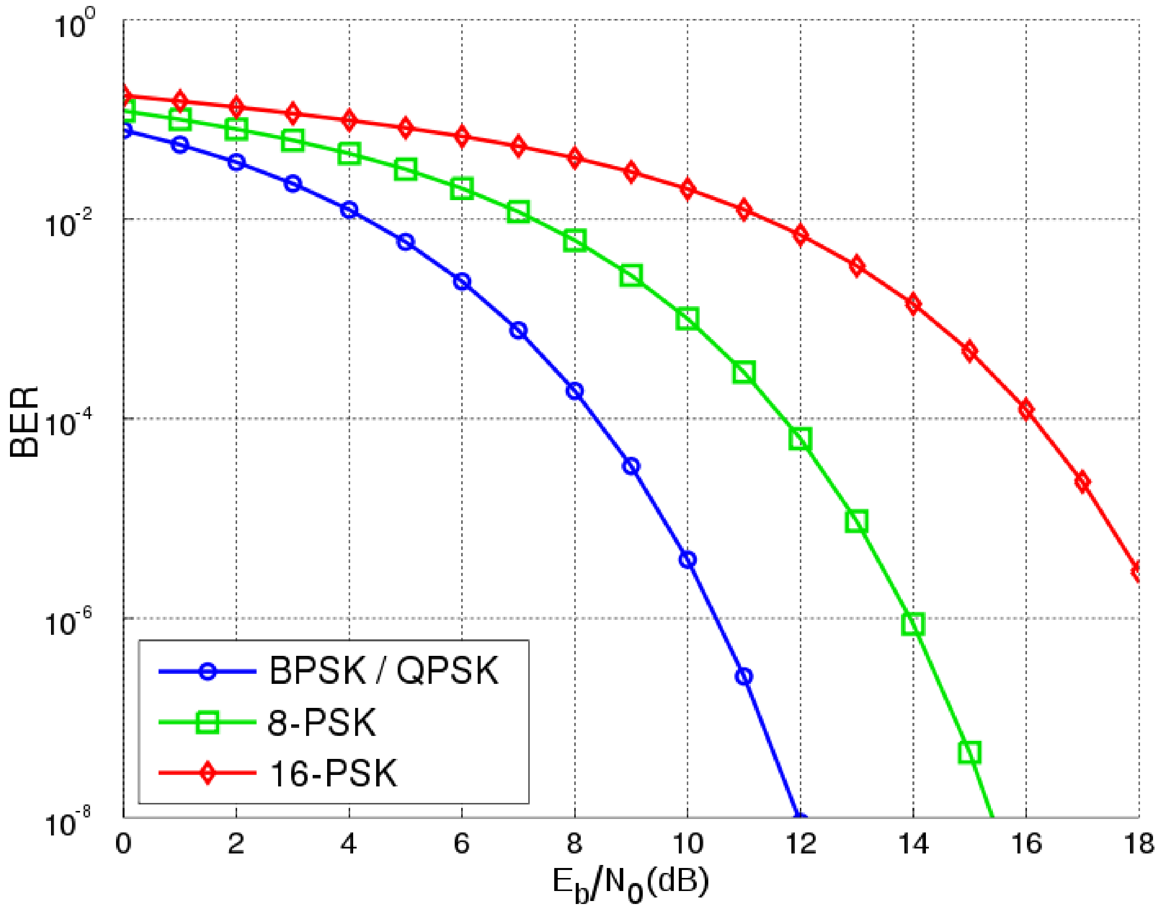
A higher steering ratio means that you have to turn the steering wheel more, to get the wheels turning, but it will be easier to turn the steering wheel. A lower steering ratio means that you have to turn the steering wheel less, to get the wheels turning, but it will be harder to turn the steering wheel. Larger and heavier vehicles will often have a higher steering ratio, which will make the steering wheel easier to turn. If a truck had a low steering ratio, it would be very hard to turn the steering wheel. In normal and lighter cars, the wheels becomes easier to turn, so the steering ratio doesn't have to be as high. In race cars the ratio becomes really low, because you want the vehicle to respond a lot quicker than in normal cars. The steering wheel will also become a lot harder to turn.

Another use of the term **steering ratio** is for the ratio between the theoretical turning radius based on ideal tire behavior and the actual turning radius based on real tire behavior. Values less than one, where the front wheel side slip is greater than the rear wheel side slip, are described as under-steering; equal to one as neutral steering; and greater than one as over-steering. Values less than zero, in which the front wheel must be turned opposite the direction of the curve due to much greater rear wheel side slip than front wheel have been described as counter-steering.

Variable-ratio steering

A variable-ratio steering, is a system that uses different ratios on the rack, in a rack and pinion steering system. At the center of the rack, the space between the teeth are smaller and the space becomes larger as the pinion moves down the rack. In the middle of the rack you'll have a higher ratio and the ratio becomes lower as you turn the steering wheel towards lock. This makes the steering less sensitive, when the steering wheel is close to its center position and makes it harder for the driver to oversteer at high speeds. As you turn the steering wheel towards lock, the wheels begins to react more to your steering input.

Eb/N0



Bit-error rate (BER) vs E_b/N_0 curves for differnt digital modulation methods is a common application example of E_b/N_0. Here an AWGN channel is assumed.

E_b/N_0 (the **energy per bit to noise power spectral density ratio**) is an important parameter in digital communication or data transmission. It is a normalized signal-to-noise ratio (SNR) measure, also known as the "SNR per bit". It is especially useful when comparing the bit error rate (BER) performance of different digital modulation schemes without taking bandwidth into account.

E_b/N_0 is equal to the SNR divided by the "gross" link spectral efficiency in (bit/s)/Hz, where the bits in this context are transmitted data bits, inclusive of error correction information and other protocol overhead. When forward error correction (FEC) is being discussed, E_b/N_0 is routinely used to refer to the energy per information bit (i.e. the energy per bit net of FEC overhead bits); in this context, E_s/N_0 is generally used to relate actual transmitted power to noise.

The noise spectral density N_0, usually expressed in units of watts per hertz, can also be seen as having dimensions of energy, or units of joules, or joules per cycle. E_b/N_0 is therefore a non-dimensional ratio.

E_b/N_0 is commonly used with modulation and coding designed for noise-limited rather than interference-limited communication, and for power-limited rather than bandwidth-limited communications. Examples of power-limited communications include deep-space and spread spectrum, and is optimized by using large bandwidths relative to the bit rate.

Relation to carrier-to-noise ratio

E_b/N_0 is closely related to the carrier-to-noise ratio (CNR or C/N), i.e. the signal-to-noise ratio (SNR) of the received signal, after the receiver filter but before detection:

$$C/N = E_b/N_0 \cdot \frac{f_b}{B}$$

where

f_b is the channel data rate (net bitrate), and
B is the channel bandwidth

The equivalent expression in logarithmic form (dB):

$$CNR_{dB} = 10\log_{10}(E_b/N_0) + 10\log_{10}\left(\frac{f_b}{B}\right),$$

Caution: Sometimes, the noise power is denoted by $N_0 / 2$ when negative frequencies and complex-valued equivalent baseband signals are considered, and in that case, there will be a 3 dB difference.

Relation to E_s/N_0

E_b/N_0 can be seen as a normalized measure of the **energy per symbol per noise power spectral density** (E_s/N_0):

$$\frac{E_b}{N_0} = \frac{E_s}{\rho N_0},$$

where E_s is the energy per symbol in joules and ρ is the nominal spectral efficiency in (bit/s)/Hz. E_s/N_0 is also commonly used in the analysis of digital modulation schemes. The two quotients are related to each other according to the following:

$$\frac{E_s}{N_0} = \frac{E_b}{N_0} \log_2 M,$$

where M is the number of alternative modulation symbols.

E_s/N_0 can further be expressed as:

$$\frac{E_s}{N_0} = \frac{C}{N}\frac{B}{f_s},$$

where

C/N is the carrier-to-noise ratio or signal-to-noise ratio.
B is the channel bandwidth in hertz.
f_s is the symbol rate in baud or symbols per second.

For a PSK, ASK or QAM modulation with pulse shaping such as raised cosine shaping, the B/f_s ratio is usually slightly larger than 1, depending of the pulse shaping filter.

Shannon limit

The Shannon–Hartley theorem says that the limit of reliable data rate of a channel depends on bandwidth and signal-to-noise ratio according to:

$$I < B \log_2 \left(1 + \frac{S}{N}\right)$$

where

I is the information rate in bits per second excluding error-correcting codes;
B is the bandwidth of the channel in hertz;
S is the total signal power (equivalent to the carrier power C); and
N is the total noise power in the bandwidth.

This equation can be used to establish a bound on E_b/N_0 for any system that achieves reliable communication, by considering a gross bit rate R equal to the net bit rate I and therefore an average energy per bit of $E_b = S/R$, with noise spectral density of $N_0 = N/B$. For this calculation, it is conventional to define a normalized rate $R_l = R/2B$, a bandwidth utilization parameter of bits per second per half hertz, or bits per dimension (a signal of bandwidth B can be encoded with $2B$ dimensions, according to the Nyquist–Shannon sampling theorem). Making appropriate substitutions, the Shannon limit is:

$$\frac{R}{B} = 2R_l < \log_2 \left(1 + 2R_l \frac{E_b}{N_0}\right)$$

Which can be solved to get the Shannon-limit bound on E_b/N_0:

$$\frac{E_b}{N_0} > \frac{2^{2R_l} - 1}{2R_l}$$

When the data rate is small compared to the bandwidth, so that R_l is near zero, the bound, sometimes called the *ultimate Shannon limit*, is:

$$\frac{E_b}{N_0} > \ln(2)$$

which corresponds to –1.59 dB.

Cutoff rate

For any given system of coding and decoding, there exists what is known as a *cutoff rate* R_0, typically corresponding to an E_b/N_0 about 2 dB above the Shannon capacity limit. The cutoff rate used to be thought of as the limit on practical error correction codes without an unbounded increase in processing complexity, but has been rendered largely obsolete by the more recent discovery of turbo codes.