Handbook of Mechanical Transmission

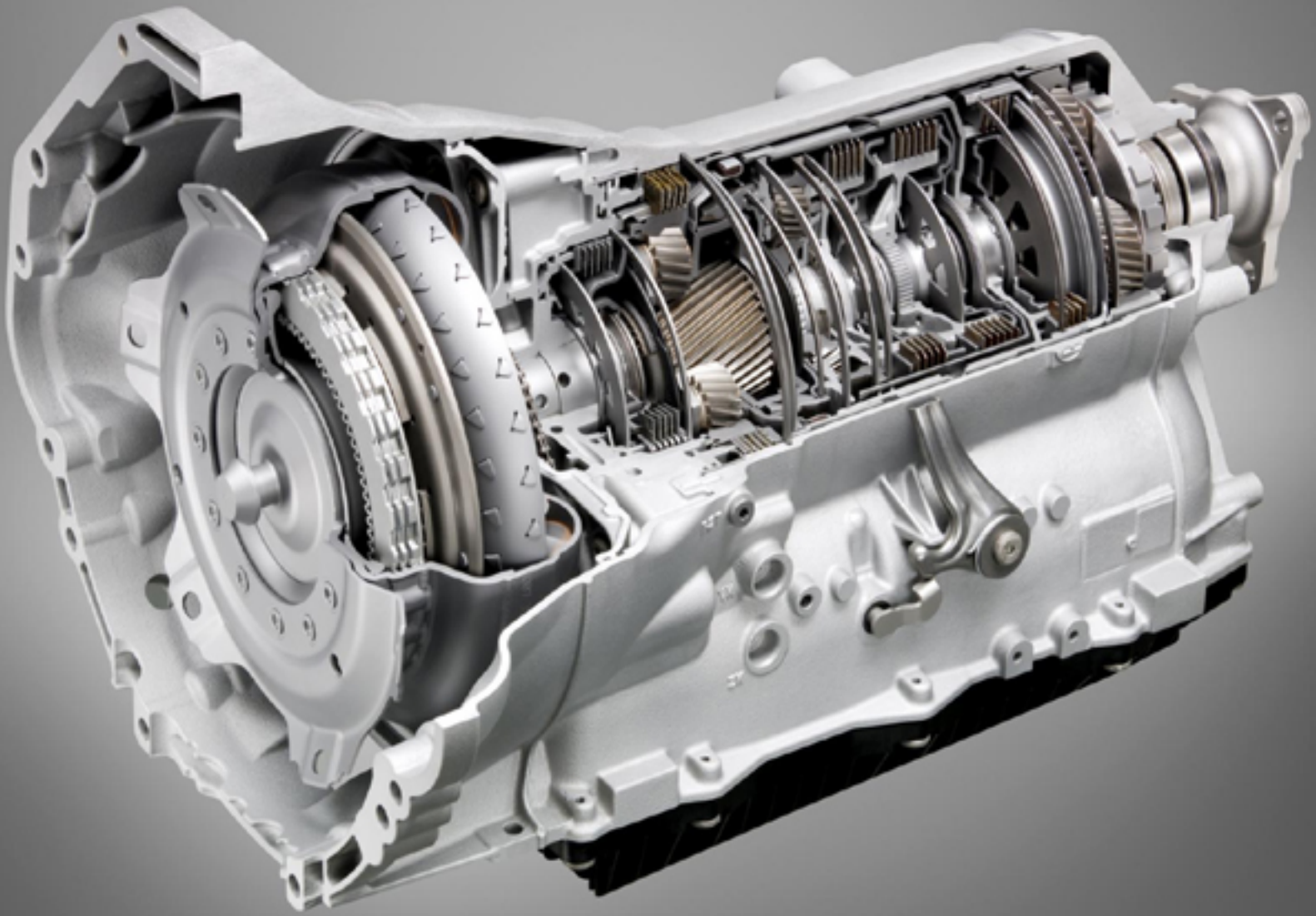

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Table of Contents

Chapter 1

Transmission (Mechanics)

A **transmission** or **gearbox** provides speed and torque conversions from a rotating power source to another device using gear ratios. In British English the term transmission refers to the whole drive train, including gearbox, clutch, prop shaft (for rear-wheel drive), differential and final drive shafts. In American English, however, the distinction is made that a gearbox is any device which converts speed and torque, whereas a transmission is a type of gearbox that can be "shifted" to dynamically change the speed:torque ratio, such as in a vehicle. The most common use is in motor vehicles, where the transmission adapts the output of the internal combustion engine to the drive wheels. Such engines need to operate at a relatively high rotational speed, which is inappropriate for starting, stopping, and slower travel. The transmission reduces the higher engine speed to the slower wheel speed, increasing torque in the process. Transmissions are also used on pedal bicycles, fixed machines, and anywhere else rotational speed and torque needs to be adapted.

Often, a transmission will have multiple gear ratios (or simply "gears"), with the ability to switch between them as speed varies. This switching may be done manually (by the operator), or automatically. Directional (forward and reverse) control may also be provided. Single-ratio transmissions also exist, which simply change the speed and torque (and sometimes direction) of motor output.

In motor vehicle applications, the transmission will generally be connected to the crankshaft of the engine. The output of the transmission is transmitted via driveshaft to one or more differentials, which in turn drive the wheels. While a differential may also provide gear reduction, its primary purpose is to change the direction of rotation.

Conventional gear/belt transmissions are not the only mechanism for speed/torque adaptation. Alternative mechanisms include torque converters and power transformation (e.g., diesel-electric transmission, hydraulic drive system, etc.). Hybrid configurations also exist.

Explanation

The main gearbox of a Bristol Sycamore helicopter

Early transmissions included the right-angle drives and other gearing in windmills, horse-powered devices, and steam engines, in support of pumping, milling, and hoisting.

Most modern gearboxes are used to increase torque while reducing the speed of a prime mover output shaft (e.g. a motor crankshaft). This means that the output shaft of a gearbox will rotate at slower rate than the input shaft, and this reduction in speed will produce a mechanical advantage, causing an increase in torque. A gearbox can be setup to do the opposite and provide an increase in shaft speed with a reduction of torque. Some of the simplest gearboxes merely change the physical direction in which power is transmitted.

Many typical automobile transmissions include the ability to select one of several different gear ratios. In this case, most of the gear ratios (often simply called "gears") are used to slow down the output speed of the engine and increase torque. However, the highest gears may be "overdrive" types that increase the output speed.

Uses

Gearboxes have found use in a wide variety of different—often stationary—applications, such as wind turbines.

Transmissions are also used in agricultural, industrial, construction, mining and automotive equipment. In addition to ordinary transmission equipped with gears, such equipment makes extensive use of the hydrostatic drive and electrical adjustable-speed drives.

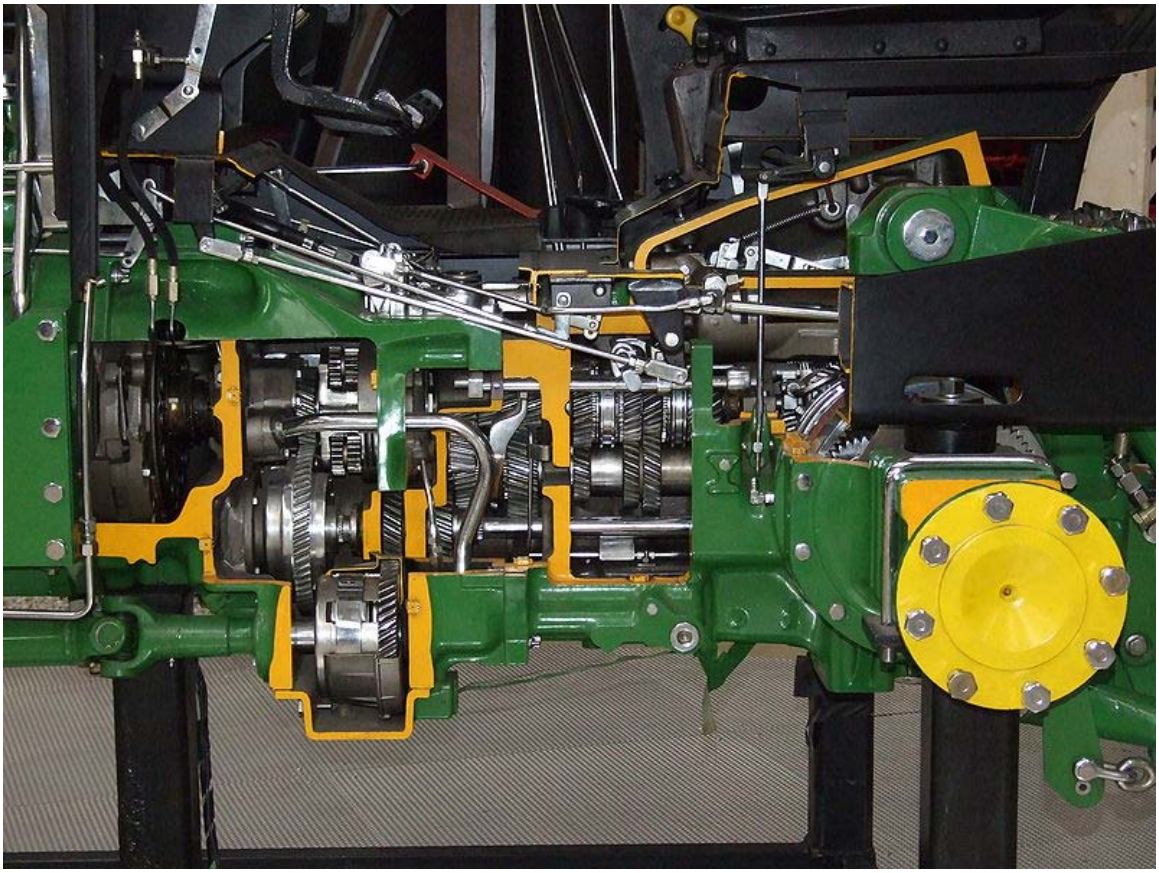
Simple

The simplest transmissions, often called gearboxes to reflect their simplicity (although complex systems are also called gearboxes in the vernacular), provide gear reduction (or, more rarely, an increase in speed), sometimes in conjunction with a right-angle change in direction of the shaft. These are often used on PTO-powered agricultural equipment, since the axial PTO shaft is at odds with the usual need for the driven shaft, which is either vertical (as with rotary mowers), or horizontally extending from one side of the implement to another (as with manure spreaders, flail mowers, and forage wagons). More complex equipment, such as silage choppers and snowblowers, have drives with outputs in more than one direction.

The gearbox in a wind turbine converts the slow, high-torque rotation of the turbine into much faster rotation of the electrical generator. These are much larger and more complicated than the PTO gearboxes in farm equipment. They weigh several tons and typically contain three stages to achieve an overall gear ratio from 40:1 to over 100:1, depending on the size of the turbine. (For aerodynamic and structural reasons, larger turbines have to turn more slowly, but the generators all have to rotate at similar speeds of several thousand rpm.) The first stage of the gearbox is usually a planetary gear, for compactness, and to distribute the enormous torque of the turbine over more teeth of the low-speed shaft. Durability of these gearboxes has been a serious problem for a long time.

Regardless of where they are used, these simple transmissions all share an important feature: the gear ratio cannot be changed during use. It is fixed at the time the transmission is constructed.

Multi-ratio systems



Tractor transmission with 16 forward and 8 backward gears

Many applications require the availability of multiple gear ratios. Often, this is to ease the starting and stopping of a mechanical system, though another important need is that of maintaining good fuel efficiency.

Automotive basics

The need for a transmission in an automobile is a consequence of the characteristics of the internal combustion engine. Engines typically operate over a range of 600 to about 7000 revolutions per minute (though this varies, and is typically less for diesel engines), while the car's wheels rotate between 0 rpm and around 1800 rpm.

Furthermore, the engine provides its highest torque outputs approximately in the middle of its range, while often the greatest torque is required when the vehicle is moving from rest or traveling slowly. Therefore, a system that transforms the engine's output so that it can supply high torque at low speeds, but also operate at highway speeds with the motor still operating within its limits, is required. Transmissions perform this transformation.

Many transmissions and gears used in automotive and truck applications are contained in a cast iron case, though more frequently aluminium is used for lower weight especially in cars. There are usually three shafts: a mainshaft, a countershaft, and an idler shaft.

The mainshaft extends outside the case in both directions: the input shaft towards the engine, and the output shaft towards the rear axle (on rear wheel drive cars- front wheel drives generally have the engine and transmission mounted transversely, the differential being part of the transmission assembly.) The shaft is suspended by the main bearings, and is split towards the input end. At the point of the split, a pilot bearing holds the shafts together. The gears and clutches ride on the mainshaft, the gears being free to turn relative to the mainshaft except when engaged by the clutches.

Types of automobile transmissions include manual, automatic or semi-automatic transmission.

Manual

A five-speed gearbox.

Manual transmission come in two basic types:

- a simple but rugged **sliding-mesh** or unsynchronized / non-synchronous system, where straight-cut spur gear sets are spinning freely, and must be synchronized by the operator matching engine revs to road speed, to avoid noisy and damaging "gear clash",

- and the now common **constant-mesh** gearboxes which can include non-synchronised, or synchronized / synchromesh systems, where diagonal cut helical (and sometimes double-helical) gear sets are constantly "meshed" together, and a dog clutch is used for changing gears. On synchromesh boxes, friction cones or "synchro-rings" are used in addition to the dog clutch.

The former type is commonly found in many forms of racing cars, older heavy-duty trucks, and some agricultural equipment.

Manual transmissions are the most common type outside North America and Australia. They are cheaper, lighter, usually give better performance, and fuel efficiency (although automatic transmissions with torque convertor lockup and advanced electronic controls can provide similar results). It is customary for new drivers to learn, and be tested, on a car with a manual gear change. In Malaysia, Denmark and Poland all cars used for testing (and because of that, virtually all those used for instruction as well) have a manual transmission. In Japan, the Philippines, Germany, Italy, Israel, the Netherlands, Belgium, New Zealand, Austria, Bulgaria, the UK , Ireland, Sweden, Estonia, France, Spain, Switzerland, the Australian states of Victoria, Western Australia and Queensland, Finland and Lithuania, a test pass using an automatic car does not entitle the driver to use a manual car on the public road; a test with a manual car is required. Manual transmissions are much more common than automatic transmissions in Asia, Africa, South America and Europe.

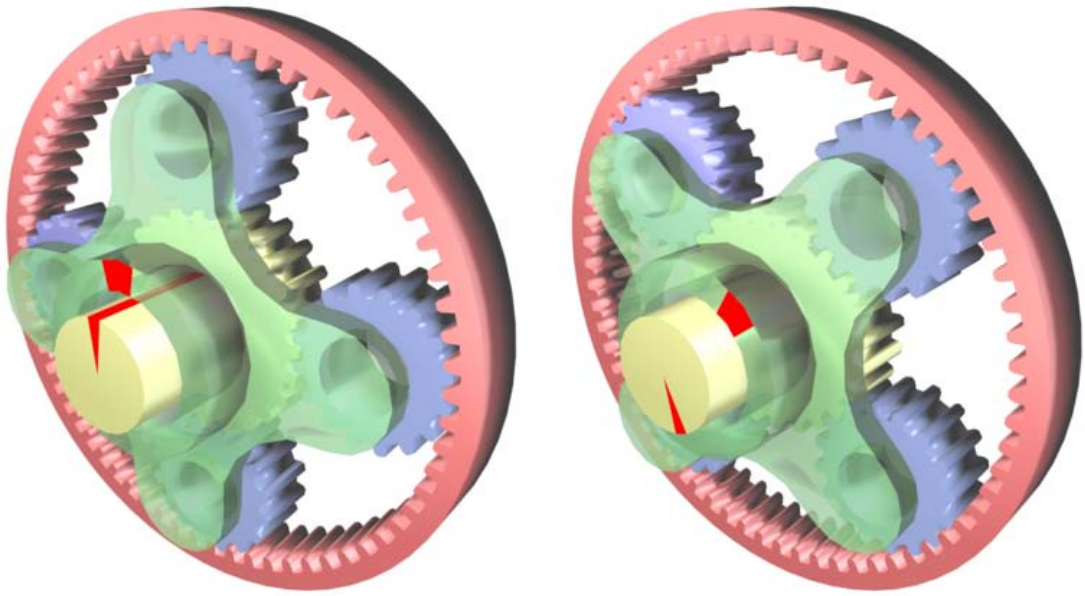
Many manual transmissions include both synchronized and unsynchronized gearing; it is not uncommon for the first/reverse gear to lack synchros. Those gears are meant to be shifted into only when the vehicle is stopped.

Some manual transmissions have an extremely low ratio for first gear, which is referred to as a "creeper gear" or "granny gear". Such gears are usually not synchronized. This feature is common on pickup trucks tailored to trailer-towing, farming, or construction-site work. During normal on-road use, the truck is usually driven without using the creeper gear at all, and second gear is used from a standing start.

Non-synchronous

There are commercial applications engineered with designs taking into account that the gear shifting will be done by an experienced operator. They are a manual transmission, but are known as non-synchronized transmissions. Dependent on country of operation, many local, regional, and national laws govern the operation of these types of vehicles. This class may include commercial, military, agricultural, or engineering vehicles. Some of these may use combinations of types for multi-purpose functions. An example would be a PTO, or *power-take-off* gear. The non-synchronous transmission type requires an understanding of gear range, torque, engine power, and multi-functional clutch and shifter functions.

Automatic



Epicyclic gearing or planetary gearing as used in an automatic transmission.

Most modern North American and Australian and many larger, high specification European and Japanese cars have an automatic transmission that will select an appropriate gear ratio without any operator intervention. They primarily use hydraulics to select gears, depending on pressure exerted by fluid within the transmission assembly. Rather than using a clutch to engage the transmission, a fluid flywheel, or torque converter is placed in between the engine and transmission. It is possible for the driver to control the number of gears in use or select reverse, though precise control of which gear is in use may or may not be possible.

Automatic transmissions are easy to use. However, in the past, automatic transmissions of this type have had a number of problems; they were complex and expensive, sometimes had reliability problems (which sometimes caused more expenses in repair), have often been less fuel-efficient than their manual counterparts (due to "slippage" in the torque converter), and their shift time was slower than a manual making them uncompetitive for racing. With the advancement of modern automatic transmissions this has changed.

Attempts to improve the fuel efficiency of automatic transmissions include the use of torque converters which lock up beyond a certain speed, or in the higher gear ratios, eliminating power loss, and overdrive gears which automatically actuate above certain speeds; in older transmissions both technologies could sometimes become intrusive, when conditions are such that they repeatedly cut in and out as speed and such load factors as grade or wind vary slightly. Current computerized transmissions possess very complex programming to both maximize fuel efficiency and eliminate any intrusiveness.

For certain applications, the slippage inherent in automatic transmissions can be advantageous; for instance, in drag racing, the automatic transmission allows the car to be stopped with the engine at a high rpm (the "stall speed") to allow for a very quick launch when the brakes are released; in fact, a common modification is to increase the stall speed of the transmission. This is even more advantageous for turbocharged engines, where the turbocharger needs to be kept spinning at high rpm by a large flow of exhaust in order to keep the boost pressure up and eliminate the turbo lag that occurs when the engine is idling and the throttle is suddenly opened.

Semi-automatic

The creation of computer control also allowed for a sort of cross-breed transmission where the car handles manipulation of the clutch automatically, but the driver can still select the gear manually if desired. This is sometimes called a "clutchless manual," or "automated manual" transmission. Many of these transmissions allow the driver to give full control to the computer. They are generally designed using manual transmission "internals", and when used in passenger cars, have synchromesh operated helical constant mesh gear sets.

Specific type of this transmission includes: Easytronic, and Geartronic.

A "dual-clutch" transmission uses two sets of internals which are alternately used, each with its own clutch, so that only the clutches are used during the actual "gearchange".

Specific type of this transmission includes: Direct-Shift Gearbox.

There are also sequential transmissions which use the rotation of a drum to switch gears.

Bicycle gearing

Shimano XT rear derailleur on a mountain bike

Bicycles usually have a system for selecting different gear ratios. There are two main types: derailleur gears and hub gears. The derailleur type is the most common, and the most visible, using sprocket gears. Typically there are several gears available on the rear sprocket assembly, attached to the rear wheel. A few more sprockets are usually added to the front assembly as well. Multiplying the number of sprocket gears in front by the number to the rear gives the number of gear ratios, often called "speeds".

Hub gears use epicyclic gearing and are enclosed within the axle of the rear wheel. Because of the small space, they typically offer fewer different speeds, although at least

one has reached 14 gear ratios and Fallbrook Technologies manufactures a transmission with technically infinite ratios.

Causes for failure of bicycle gearing include: worn teeth, damage caused by a faulty chain, damage due to thermal expansion, broken teeth due to excessive pedaling force, interference by foreign objects, and loss of lubrication due to negligence.

Uncommon types

Dual clutch transmission

This arrangement is also sometimes known as a direct shift gearbox or powershift gearbox. It seeks to combine the advantages of a conventional manual shift with the qualities of a modern automatic transmission by providing different clutches for odd and even speed selector gears. When changing gear, the engine torque is transferred from one gear to the other continuously, so providing gentle, smooth gear changes without either losing power or jerking the vehicle. Gear selection may be manual, automatic (depending on throttle/speed sensors), or a 'sports' version combining both options.

Continuously variable

The Continuously Variable Transmission (CVT) is a transmission in which the ratio of the rotational speeds of two shafts, as the input shaft and output shaft of a vehicle or other machine, can be varied continuously within a given range, providing an infinite number of possible ratios.

The continuously variable transmission (CVT) should not be confused with the Infinitely Variable Transmission (IVT).

The other mechanical transmissions described above only allow a few different gear ratios to be selected, but this type of transmission essentially has an infinite number of ratios available within a finite range. The continuously variable transmission allows the relationship between the speed of the engine and the speed of the wheels to be selected within a continuous range. This can provide even better fuel economy if the engine is constantly running at a single speed. The transmission is in theory capable of a better user experience, without the rise and fall in speed of an engine, and the jerk felt when poorly changing gears.

Infinitely variable

The IVT is a specific type of CVT that has an infinite range of input/output ratios in addition to its infinite number of possible ratios; this qualification for the IVT implies that its range of ratios includes a zero output/input ratio that can be continuously approached from a defined 'higher' ratio. A zero output implies an infinite input, which can be continuously approached from a given finite input value with an IVT. [Note: remember that so-called 'low' gears are a reference to low ratios of output/input, which

have high input/output ratios that are taken to the extreme with IVTs, resulting in a 'neutral', or non-driving 'low' gear limit.]

Most (if not all) IVTs result from the combination of a CVT with an epicyclic gear system (which is also known as a planetary gear system) that facilitates the subtraction of one speed from another speed within the set of input and planetary gear rotations. This subtraction only needs to result in a continuous range of values that includes a zero output; the maximum output/input ratio can be arbitrarily chosen from infinite practical possibilities through selection of extraneous input or output gear, pulley or sprocket sizes without affecting the zero output or the continuity of the whole system. Importantly, the IVT is distinguished as being 'infinite' in its ratio of high gear to low gear within its range; high gear is infinite times higher than low gear. The IVT is always engaged, even during its zero output adjustment.

The term 'infinitely variable transmission' does not imply reverse direction, disengagement, automatic operation, or any other quality except ratio selectability within a continuous range of input/output ratios from a defined minimum to an undefined, 'infinite' maximum. This means continuous range from a defined output/input to zero output/input ratio.

Electric variable

The Electric Variable Transmission (EVT) is a transmission that achieves CVT action and in addition can use separate power inputs to produce one output. An EVT is usually designed around an epicyclic differential gear system (also known as a planetary gear system). The epicyclic gear acts as a differential, performing a "power-split" function; a portion of the mechanical power is carried directly through the gear set (the "mechanical path"). The rest of the power is converted to and from electrical energy by electric motor-generators (the "electrical path"). Hence, the EVT is a class of Power Split Transmission (PST).

Many EVTs are linked to batteries or other electrical energy storage devices. This enables them to store or draw electrical power for better operation under various conditions.

The pair of motor/generators forms an Electric Transmission in its own right, but at a lower capacity, than the EVT it is contained within. Generally the Electric Transmission capacity within the EVT is a quarter to a half of the capacity of the EVT. An EVT is often preferable to a pure electrical transmission because the mechanical transmission is cheaper, more compact, and more efficient than the electrical path.

The EVT linked to a battery is the essential method for transmitting power in some hybrid vehicles, enabling an Internal Combustion Engine (ICE) to be used in conjunction with motor/generators for vehicle propulsion. Vehicle speed is controlled primarily by adjusting the amount of power flowing through the electrical as opposed to the mechanical path. The EVT may be used to generate electrical power for storage in a battery, especially through 'regenerative braking' during deceleration. Various

configurations of power generation, usage and balance can be implemented with an EVT, enabling great flexibility in propelling hybrid vehicles.

The Toyota single mode hybrid and General Motor 2 Mode hybrid are production systems that use EVTs. The Toyota system is in the Prius, Highlander, and Lexus RX400h and GS450h models. The GM system is used in the Allison Bus hybrid powertrains and the Tahoe and Yukon models. The Toyota system uses one power-split epicyclic differential gearing system over all driving conditions and is sized with an electrical path rated at approximately half the capacity of the EVT. The GM system uses two different EVT ranges: one designed for lower speeds with greater mechanical advantage, and one designed for higher speeds. The electrical path is rated at approximately a quarter of the capacity of the EVT. Other arrangements are possible and applications of EVTs are growing rapidly in number and variety.

EVTs are capable of continuously modulating output/input speed ratios like mechanical CVTs, but offer the distinct difference and benefit of being able to also apportion power from two different sources to one output.

Hydrostatic

Hydrostatic transmissions transmit all power hydraulically, using the components of hydraulic machinery. Hydrostatic transmissions do not make use of the hydrodynamic forces of the fluid flow. There is no solid coupling of the input and output. The transmission input drive is a central hydraulic pump and final drive unit(s) is/are a hydraulic motor, or hydraulic cylinder (see:*swashplate*). Both components can be placed physically far apart on the machine, being connected only by flexible hoses. Hydrostatic drive systems are used on excavators, lawn tractors, forklifts, winch drive systems, heavy lift equipment, agricultural machinery, etc. An arrangement for motor-vehicle transmission was probably used on the Ferguson *F-1* P99 racing car in about 1961.

The Human Friendly Transmission of the Honda DN-01 is hydrostatic.

Hydrodynamic

If the hydraulic pump and/or hydraulic motor make use of the hydrodynamic effects of the fluid flow, i.e. pressure due to a change in the fluid's momentum as it flows through vanes in a turbine. The pump and motor usually consist of rotating vanes without seals and are typically placed in close proximity. The transmission ratio can be made to vary by means of additional rotating vanes, an effect similar to varying the pitch of an airplane propeller.

The torque converter in most automotive automatic transmissions is, in itself, a hydrodynamic transmission.

It was possible to drive the Dynaflow transmission without shifting the mechanical gears.

Hydrodynamic transmissions are used in many passenger rail vehicles. In this application the advantage of smooth power delivery may outweigh the reduced efficiency caused by turbulence energy losses in the fluid.

Electric

Electric transmissions convert the mechanical power of the engine(s) to electricity with electric generators and convert it back to mechanical power with electric motors. Electrical or electronic adjustable-speed drive control systems are used to control the speed and torque of the motors. If the generators are driven by turbines, such arrangements are called turbo-electric. Likewise installations powered by diesel-engines are called diesel-electric. Diesel-electric arrangements are used on many railway locomotives, ships and large mining trucks.

Virtual transmission

Virtual Transmission allows for the same traction motor to be both a low-speed high torque and high-speed electric motor, using the winding/software that runs on the new electric motors. This virtual transmission will require less complex engineering, and less weight. The alternator and starter for the Chevrolet Volt can be combined into a single armature, smaller and lighter than each alternator and starter individually.

Chapter 2

Manual Transmission

A floor-mounted gear shift lever in a modern passenger car with a manual transmission

A **manual transmission**, also known as a **manual gearbox** or **standard transmission** (informally, a "manual", "straight shift", "stick (shift)" (US), or "straight drive") is a type of transmission used in motor vehicle applications. It generally uses a driver-operated clutch, typically operated by a pedal or lever, for regulating torque transfer from the internal combustion engine to the transmission, and a gear stick, either operated by hand (as in a car) or by foot (as on a motorcycle).

A conventional manual transmission is frequently the base equipment in a car; other options include automated transmissions such as an automatic transmission (often a manumatic), a semi-automatic transmission, or a continuously variable transmission (CVT).

Overview

Manual transmissions often feature a driver-operated clutch and a movable gear stick. Most automobile manual transmissions allow the driver to select any forward gear ratio ("gear") at any time, but some, such as those commonly mounted on motorcycles and some types of racing cars, only allow the driver to select the next-higher or next-lower gear. This type of transmission is sometimes called a sequential manual transmission. Sequential transmissions are commonly used in auto racing for their ability to make quick shifts.

Manual transmissions are characterized by gear ratios that are selectable by locking selected gear pairs to the output shaft inside the transmission. Conversely, most automatic transmissions feature epicyclic (planetary) gearing controlled by brake bands and/or clutch packs to select gear ratio. Automatic transmissions that allow the driver to manually select the current gear are called Manumatics. A manual-style transmission operated by computer is often called an *automated* transmission rather than an *automatic*.

Contemporary automobile manual transmissions typically use four to six forward gears and one reverse gear, although automobile manual transmissions have been built with as few as two and as many as eight gears. Transmission for heavy trucks and other heavy equipment usually have at least 9 gears so the transmission can offer both a wide range of gears and close gear ratios to keep the engine running in the power band. Some heavy vehicle transmissions have dozens of gears, but many are duplicates, introduced as an accident of combining gear sets, or introduced to simplify shifting. Some manuals are referred to by the number of forward gears they offer (e.g., 5-speed) as a way of distinguishing between automatic or other available manual transmissions. Similarly, a 5-speed automatic transmission is referred to as a "5-speed automatic."

Unsynchronized transmission

The earliest form of a manual transmission is thought to have been invented by Louis-René Panhard and Emile Levassor in the late 19th century. This type of transmission offered multiple gear ratios and, in most cases, reverse. The gears were typically engaged by sliding them on their shafts (hence the phrase *shifting gears*), which required a lot of careful timing and throttle manipulation when shifting, so that the gears would be spinning at roughly the same speed when engaged; otherwise, the teeth would refuse to mesh. These transmissions are called *sliding mesh* transmissions and sometimes called a crash box, because of the difficulty in changing gears and the loud grinding sound that often accompanied. Newer manual transmissions on cars, instead have all gears mesh at all times; these are referred to as *constant-mesh* transmissions, with "synchro-mesh" being a further refinement of the constant mesh principle.

In both types, a particular gear combination can only be engaged when the two parts to engage (either gears or clutches) are at the same speed. To shift to a higher gear, the transmission is put in neutral and the engine allowed to slow down until the transmission parts for the next gear are at a proper speed to engage. The vehicle also slows while in neutral and that slows other transmission parts, so the time in neutral depends on the grade, wind, and other such factors. To shift to a lower gear, the transmission is put in neutral and the throttle is used to speed up the engine and thus the relevant transmission parts, to match speeds for engaging the next lower gear. For both upshifts and downshifts, the clutch is released (engaged) while in neutral. Some drivers use the clutch only for starting from a stop, and shifts are done without the clutch. Other drivers will depress (disengage) the clutch, shift to neutral, then engage the clutch momentarily to force transmission parts to match the engine speed, then depress the clutch again to shift to the next gear, a process called double clutching. Double clutching is easier to get smooth, as speeds that are close but not quite matched need to speed up or slow down only transmission parts, whereas with the clutch engaged to the engine, mismatched speeds are fighting the rotational inertia and power of the engine.

Even though automobile and light truck transmissions are now almost universally synchronised, transmissions for heavy trucks and machinery, motorcycles, and for dedicated racing are usually not. Non-synchronized transmission designs are used for several reasons. The friction material, such as brass, in synchronizers is more prone to wear and breakage than gears, which are forged steel, and the simplicity of the mechanism improves reliability and reduces cost. In addition, the process of shifting a synchromesh transmission is slower than that of shifting a non-synchromesh transmission. For racing of production-based transmissions, sometimes half the teeth (or *dogs*) on the synchros are removed to speed the shifting process, at the expense of greater wear.

Heavy duty trucks often use unsynchronized transmissions. Military trucks usually have synchronized transmissions, allowing untrained personnel to operate them in emergencies. In the United States, traffic safety rules refer to non-synchronous transmissions in classes of larger commercial motor vehicles. In Europe, heavy duty trucks use synchronized gearboxes as standard.

Similarly, most modern motorcycles use unsynchronized transmissions as synchronizers are generally not necessary or desirable. Their low gear inertias and higher strengths mean that forcing the gears to alter speed is not damaging, and the pedal operated selector on modern motorcycles is not conducive to having the long shift time of a synchronized gearbox. Because of this, it is necessary to synchronize gear speeds by blipping the throttle when shifting into a lower gear on a motorcycle.

Synchronised transmission

Top and side view of a typical manual transmission, in this case a Ford Toploader, used in cars with external floor shifters.

Most modern cars are fitted with a synchronised gear box. Transmission gears are always in mesh and rotating, but gears on one shaft can freely rotate or be locked to the shaft. The locking mechanism for a gear consists of a collar (or *dog collar*) on the shaft which is able to slide sideways so that teeth (or *dogs*) on its inner surface bridge two circular rings with teeth on their outer circumference: one attached to the gear, one to the shaft. When the rings are bridged by the collar, that particular gear is rotationally locked to the shaft and determines the output speed of the transmission. The gearshift lever manipulates the collars using a set of linkages, so arranged so that one collar may be permitted to lock only one gear at any one time; when "shifting gears," the locking collar from one gear is disengaged before that of another engaged. One collar often serves for two gears; sliding in one direction selects one transmission speed, in the other direction selects another.

In a synchromesh gearbox, to correctly match the speed of the gear to that of the shaft as the gear is engaged, the collar initially applies a force to a cone-shaped brass clutch attached to the gear, which brings the speeds to match prior to the collar locking into place. The collar is prevented from bridging the locking rings when the speeds are mismatched by synchro rings (also called blocker rings or baulk rings, with the latter being spelt *balk* in the U.S.). The synchro ring rotates slightly due to the frictional torque from the cone clutch. In this position, the dog clutch is prevented from engaging. The brass clutch ring gradually causes parts to spin at the same speed. When they do spin the same speed, there is no more torque from the cone clutch, and the dog clutch is allowed

to fall in to engagement. In a modern gearbox, the action of all of these components is so smooth and fast it is hardly noticed.

The modern cone system was developed by Porsche and introduced in the 1952 Porsche 356; cone synchronisers were called *Porsche-type* for many years after this. In the early 1950s, only the second-third shift was synchromesh in most cars, requiring only a single synchro and a simple linkage; drivers' manuals in cars suggested that if the driver needed to shift from second to first, it was best to come to a complete stop then shift into first and start up again. With continuing sophistication of mechanical development, however, fully synchromesh transmissions with three speeds, then four speeds, and then five speeds, became universal by the 1980s. Many modern manual transmission cars, especially sports cars, now offer six speeds.

Reverse gear, however, is usually not synchromesh, as there is only one reverse gear in the normal automotive transmission and changing gears into reverse while moving is not required. Among the cars that have synchromesh in reverse are the 1995-2000 Ford Contour and Mercury Mystique, '00-'05 Chevrolet Cavalier, Mercedes 190 2.3-16, the V6 equipped Alfa Romeo GTV/Spider (916), certain Chrysler, Jeep, and GM products which use the New Venture NV3500 and NV3550 units, the European Ford Sierra and Granada/Scorpio equipped with the MT75 gearbox, the Volvo 850, and almost all Lamborghinis and BMWs.

Internals

Shafts

Like other transmissions, a manual transmission has several shafts with various gears and other components attached to them. Typically, a rear-wheel-drive transmission has three shafts: an input shaft, a *countershaft* and an output shaft. The countershaft is sometimes called a *layshaft*.

In a rear-wheel-drive transmission, the input and output shaft lie along the same line, and may in fact be combined into a single shaft within the transmission. This single shaft is called a *mainshaft*. The input and output ends of this combined shaft rotate independently, at different speeds, which is possible because one piece slides into a hollow bore in the other piece, where it is supported by a bearing. Sometimes the term *mainshaft* refers to just the input shaft or just the output shaft, rather than the entire assembly.

In some transmissions, it's possible for the input and output components of the mainshaft to be locked together to create a 1:1 gear ratio, causing the power flow to bypass the countershaft. The mainshaft then behaves like a single, solid shaft, a situation referred to as *direct drive*.

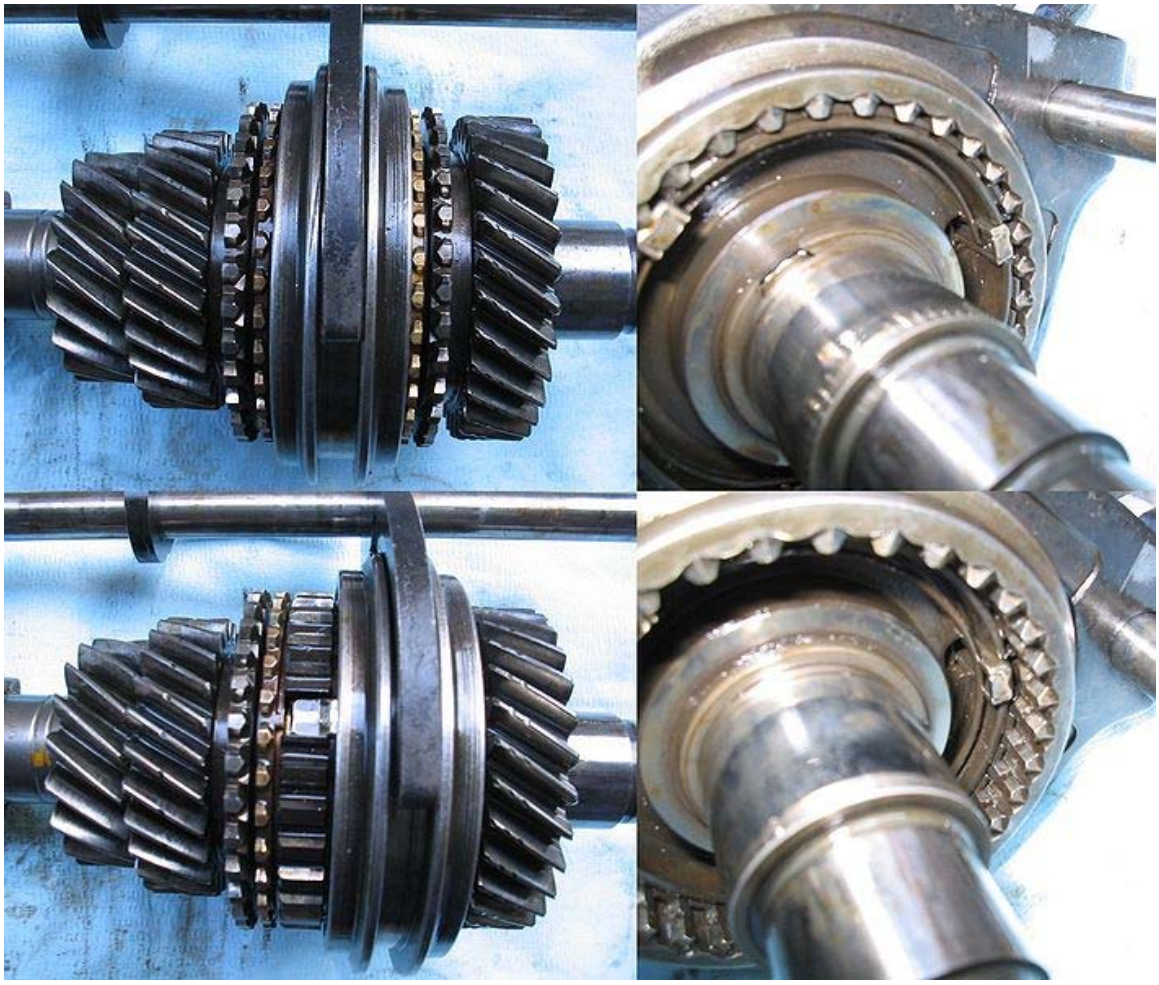
Even in transmissions that do not feature direct drive, it's an advantage for the input and output to lie along the same line, because this reduces the amount of torsion that the transmission case has to bear.

Under one possible design, the transmission's input shaft has just one pinion gear, which drives the countershaft. Along the countershaft are mounted gears of various sizes, which rotate when the input shaft rotates. These gears correspond to the forward speeds and reverse. Each of the forward gears on the countershaft is permanently meshed with a corresponding gear on the output shaft. However, these driven gears are not rigidly attached to the output shaft: although the shaft runs through them, they spin independently of it, which is made possible by bearings in their hubs.

Most front-wheel-drive transmissions for transverse engine mounting are designed differently. For one thing, they have an integral final drive and differential. For another, they usually have only two shafts; input and countershaft, sometimes called input and output. The input shaft runs the whole length of the gearbox, and there is no separate input pinion. At the end of the second (counter/output) shaft is a pinion gear that mates with the ring gear on the differential.

Front-wheel and rear-wheel-drive transmissions operate similarly. When the transmission is in neutral, and the clutch is disengaged, the input shaft, clutch disk and countershaft can continue to rotate under their own inertia. In this state, the engine, the input shaft and clutch, and the output shaft all rotate independently.

Dog clutch



Dog clutches. The gear-like teeth ("dogs", right-side images) engage and disengage with each other.

Among many different types of clutches, a dog clutch provides non-slip coupling of two rotating members. It is not at all suited to intentional slipping, in contrast with the foot-operated friction clutch of a manual-transmission car.

The gear selector does not engage or disengage the actual gear teeth which are permanently meshed. Rather, the action of the gear selector is to lock one of the freely spinning gears to the shaft that runs through its hub. The shaft then spins together with that gear. The output shaft's speed relative to the countershaft is determined by the ratio of the two gears: the one permanently attached to the countershaft, and that gear's mate which is now locked to the output shaft.

Locking the output shaft with a gear is achieved by means of a dog clutch selector. The dog clutch is a sliding selector mechanism which is splined to the output shaft, meaning that its hub has teeth that fit into slots (splines) on the shaft, forcing that shaft to rotate

with it. However, the splines allow the selector to move back and forth on the shaft, which happens when it is pushed by a selector fork that is linked to the gear lever. The fork does not rotate, so it is attached to a collar bearing on the selector. The selector is typically symmetric: it slides between two gears and has a synchromesh and teeth on each side in order to lock either gear to the shaft.

Synchromesh

Synchronizer rings

If the teeth, the so-called dog teeth, make contact with the gear, but the two parts are spinning at different speeds, the teeth will fail to engage and a loud grinding sound will be heard as they clatter together. For this reason, a modern dog clutch in an automobile has a synchronizer mechanism or *synchromesh*, which consists of a cone clutch and blocking ring. Before the teeth can engage, the cone clutch engages first which brings the selector and gear to the same speed using friction. Moreover, until synchronization occurs, the teeth are prevented from making contact, because further motion of the

selector is prevented by a *blocker* (or *baulk*) ring. When synchronization occurs, friction on the blocker ring is relieved and it twists slightly, bringing into alignment certain grooves and notches that allow further passage of the selector which brings the teeth together. Of course, the exact design of the synchronizer varies from manufacturer to manufacturer.

The synchronizer has to change the momentum of the entire input shaft and clutch disk. Additionally, it can be abused by exposure to the momentum and power of the engine itself, which is what happens when attempts are made to select a gear without fully disengaging the clutch. This causes extra wear on the rings and sleeves, reducing their service life. When an experimenting driver tries to "match the revs" on a synchronized transmission and force it into gear without using the clutch, the synchronizer will make up for any discrepancy in RPM. The success in engaging the gear without clutching can deceive the driver into thinking that the RPM of the layshaft and transmission were actually exactly matched. Nevertheless, approximate rev. matching *with clutching* can decrease the general delta between layshaft and transmission and decrease synchro wear.

Reverse

The previous discussion normally applies only to the forward gears. The implementation of the reverse gear is usually different, implemented in the following way to reduce the cost of the transmission. Reverse is also a pair of gears: one gear on the countershaft and one on the output shaft. However, whereas all the forward gears are always meshed together, there is a gap between the reverse gears. Moreover, they are both attached to their shafts: neither one rotates freely about the shaft. What happens when reverse is selected is that a small gear, called an *idler gear* or *reverse idler*, is slid between them. The idler has teeth which mesh with both gears, and thus it couples these gears together and reverses the direction of rotation without changing the gear ratio.

In other words, when reverse gear is selected, it is in fact *actual* gear teeth that are being meshed, with no aid from a synchronization mechanism. For this reason, the output shaft must not be rotating when reverse is selected: the car must be stopped. In order that reverse can be selected without grinding even if the input shaft is spinning inertially, there may be a mechanism to stop the input shaft from spinning. The driver brings the vehicle to a stop, and selects reverse. As that selection is made, some mechanism in the transmission stops the input shaft. Both gears are stopped and the idler can be inserted between them. There is a clear description of such a mechanism in the Honda Civic 1996-1998 Service Manual, which refers to it as a "noise reduction system":

Whenever the clutch pedal is depressed to shift into reverse, the mainshaft continues to rotate because of its inertia. The resulting speed difference between mainshaft and reverse idler gear produces gear noise [grinding]. The reverse gear noise reduction system employs a cam plate which was added to the reverse shift holder. When shifting into reverse, the 5th/reverse shift piece, connected to the shift lever, rotates the cam plate. This causes the 5th synchro set to stop the rotating mainshaft.

A reverse gear implemented this way makes a loud whining sound, which is not normally heard in the forward gears. The teeth on the forward gears of most consumer automobiles are helically cut. When helical gears rotate, there is constant contact between gears, which results in quiet operation. In spite of all forward gears being always meshed, they do not make a sound that can be easily heard above the engine noise. By contrast, most reverse gears are spur gears, meaning that they have straight teeth, in order to allow for the sliding engagement of the idler, which is difficult with helical gears. The teeth of spur gears clatter together when the gears spin, generating a characteristic whine.

It is clear that the spur gear design of reverse gear represents some compromises (less robust, unsynchronized engagement and loud noise) which are acceptable due to the relatively small amount of driving that takes place in reverse. The gearbox of the classic SAAB 900 is a notable example of a gearbox with a helical reverse gear engaged in the same unsynchronized manner as the spur gears described above. Its strange design allows reverse to share cogs with first gear, and is exceptionally quiet, but results in difficult engagement and unreliable operation. However, many modern transmissions now include a reverse gear synchronizer and helical gearing.

Design variations

Gear variety

Manual transmissions in passenger vehicles are often equipped with 4, 5, or more recently 6 forward gears in conventional manual transmissions with a gear stick, and up to 8 forward gears in semi-automatic transmissions. Nearly all have one reverse gear. In three or four speed transmissions, in most cases, the topmost gear is *direct* (i.e., a 1:1 ratio). For five speed or higher transmissions, the highest gear is usually an overdrive gear, with a ratio of less than 1:1. Older cars were generally equipped with 3-speed transmissions, or 4-speed transmissions for high performance models and 5-speeds for the most sophisticated of automobiles; in the 1970s, 5-speed transmissions began to appear in low priced mass market automobiles and even compact pickup trucks, pioneered by Toyota (who advertised the fact by giving each model the suffix *SR5* as it acquired the fifth speed). Today, mass market automotive manual transmissions are essentially all 5-speeds, with 6-speed transmissions beginning to emerge in high performance vehicles in the early 1990s, and recently beginning to be offered on some high-efficiency and conventional passenger cars. Some 7-speed manual-derived transmissions are offered on high-end performance cars, such as the Bugatti Veyron 16.4, or the BMW M5. Both of these cars feature a paddle shifter. Recently, even 8-speed transmissions were being offered, such as in the Lexus IS F, and in 2012 Mercedes-Benz plan to introduce a 9-speed gearbox.

External overdrive

On earlier models with three or four forward speeds, the lack of an overdrive ratio for relaxed and fuel-efficient highway cruising was often filled by incorporating a separate

overdrive unit in the rear housing of the transmission. This unit was separately actuated by a knob or button, often incorporated into the gearshift knob.

Shaft and gear configuration

On a conventional rear-drive transmission, there are three basic shafts; the input, the output, and the countershaft. The input and output together are called the *mainshaft*, since they are joined inside the transmission so they appear to be a single shaft, although they rotate totally independently of each other. The input length of this shaft is much shorter than the output shaft. Parallel to the mainshaft is the countershaft. There are a number of gears fixed along the countershaft, and matching gears along the output shaft, although these are not fixed, and rotate independently of the output shaft. There are sliding *dog collars*, or *dog clutches*, between the gears on the output shaft, and to engage a gear to the shaft, the collar slides into the space between the shaft and the inside space of the gear, thus rotating the shaft as well. One collar is usually mounted between two gears, and slides both ways to engage one or the other gears, so on a four speed there would be two collars. A front-drive transmission is basically the same, but may be simplified. There often are two shafts, the input and the output, but depending on the direction of rotation of the engine, three may be required. Rather than the input shaft driving the countershaft with a pinion gear, the input shaft takes over the countershaft's job, and the output shaft runs parallel to it. The gears are positioned and engaged just as they are on the countershaft and output shaft of a rear-drive. This merely eliminates one major component, the pinion gear. Part of the reason that the input and output are in-line on a rear drive unit is to relieve torsional stress on the transmission and mountings, but this isn't an issue in a front-drive as the gearbox is integrated into the transaxle.

The basic process is not universal. The fixed and free gears can be mounted on either the input or output shaft, or both.

The distribution of the shifters is also a matter of design; it need not be the case that all of the free-rotating gears with selectors are on one shaft, and the permanently splined gears on the other. For instance a five speed transmission might have the first-to-second selectors on the countershaft, but the third-to-fourth selector and the fifth selector on the mainshaft, which is the configuration in the 1998 Honda Civic. This means that when the car is stopped and idling in neutral with the clutch engaged and the input shaft spinning, the third, fourth and fifth gear pairs do not rotate.

In some transmission designs (Volvo 850 and V/S70 series, for example) there are actually two countershafts, both driving an output pinion meshing with the front-wheel-drive transaxle's ring gear. This allows the transmission designer to make the transmission narrower, since each countershaft need only be half as long as a traditional countershaft with four gears and two shifters.

Clutch

In all vehicles using a transmission (virtually all modern vehicles), a coupling device is used to separate the engine and transmission when necessary. The clutch accomplishes this in manual transmissions. Without it, the engine and tires would at all times be inextricably linked, and any time the vehicle stopped the engine would stall. Without the clutch, changing gears would be very difficult, even with the vehicle moving already: deselecting a gear while the transmission is under load requires considerable force, and selecting a gear requires the revolution speed of the engine to be held at a very precise value which depends on the vehicle speed and desired gear. In a car the clutch is usually operated by a pedal; on a motorcycle, a lever on the left handlebar serves the purpose.

- When the clutch pedal is fully depressed, the clutch is fully disengaged, and no torque is transferred from the engine to the transmission (and by extension to the drive wheels). In this uncoupled state it is possible to select gears or to stop the car without stopping the engine.
- When the clutch pedal is fully released, the clutch is fully engaged, and practically all of the engine's torque is transferred. In this coupled state, the clutch does not slip, but rather acts as rigid coupling, and power is transmitted to the wheels with minimal practical waste heat.
- Between these extremes of engagement and disengagement the clutch slips to varying degrees. When the clutch slips it still transmits torque despite the difference in speeds between the engine crankshaft and the transmission input. Because this torque is transmitted by means of friction rather than direct mechanical contact, considerable power is wasted as heat (which is dissipated by the clutch). Properly applied, slip allows the vehicle to be started from a standstill, and when it is already moving, allows the engine rotation to gradually adjust to a newly selected gear ratio.
- Learning to use the clutch efficiently requires the development of muscle memory and a level of coordination analogous to that required to learn a musical instrument or to play a sport.
- A rider of a highly-tuned motocross or off-road motorcycle may "hit" or "fan" the clutch when exiting corners to assist the engine in revving to the point where it delivers the most power.

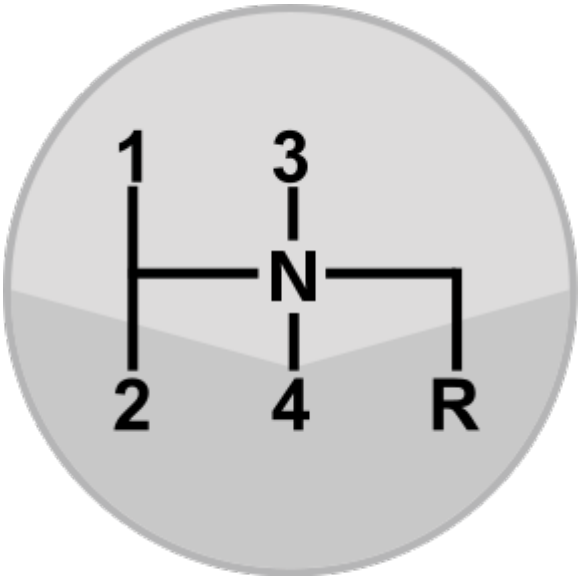
Gear shift types

Floor-mounted shifter

A 5 speed gear lever

In many modern passenger cars, gears are selected by manipulating a lever connected to the transmission via linkage or cables and mounted on the floor of the automobile. This is called a **gear stick**, **shift stick**, **gearshift**, **gear lever**, **gear selector**, or **shifter**. Moving the lever forward, backward, left, and right into specific positions selects particular gears.

A sample layout of a *four-speed* transmission is shown below. **N** marks *neutral*, the position wherein no gears are engaged and the engine is decoupled from the vehicle's drive wheels. In reality, the entire horizontal line is a neutral position, although the shifter is usually equipped with springs so that it will return to the N position if not moved to another gear. The **R** marks reverse, the gear position used for moving the vehicle rearward.

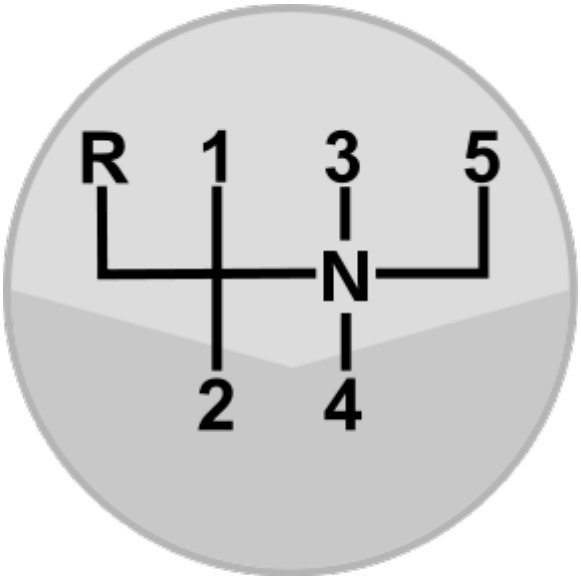


This layout is called the **shift pattern**. Because of the shift quadrants, the basic arrangement is often called an *H-pattern*. The shift pattern is usually molded or printed on or near the gear knob. While the layout for gears one through four is nearly universal, the location of reverse is not. Depending on the particular transmission design, reverse may be located at the upper left extent of the shift pattern, at the lower left, at the lower right, or at the upper right. There is usually a mechanism that only allows selection of reverse from the neutral position, or a reverse blockout that must be released by depressing the spring-loaded gear knob or lifting a spring-loaded collar on the shift stick, to reduce the likelihood that reverse will be inadvertently selected by the driver.

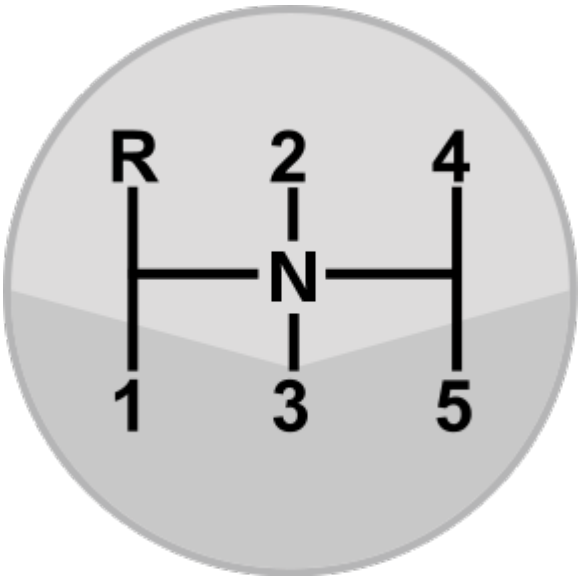
This is the most common five-speed shift pattern:

This layout is reasonably intuitive because it starts at the upper left and works left to right, top to bottom, with reverse at the end of the sequence and toward the rear of the car.

This is another five-speed shift pattern, which can be found in Saabs, BMWs, some Audis, Eagle, Volvos, Volkswagens, Škodas, Opels, Hyundais, most Renaults, some diesel Fords, and more:



Dog-leg first shift patterns are used on many race cars and on older road vehicles with three-speed transmissions:

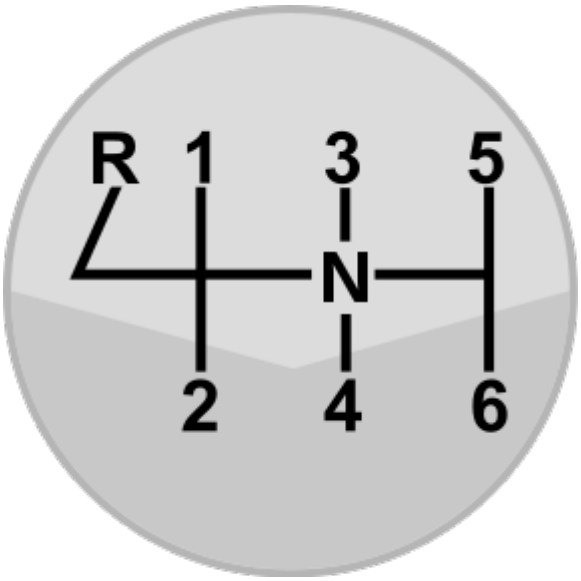


The name derives from the up-and-over path between first and second gears. Its use is common in race cars and sports cars, but is diminishing as six speed and sequential gearboxes are becoming more common. Having first gear across the dog leg is beneficial as first gear is traditionally only used for getting the car moving and hence it allows second and third gears to be aligned fore and aft of each other, which facilitates shifting

between the two. As most racing gearboxes are non-synchromesh there is no appreciable delay when upshifting from first through the dog leg into second.

This gear pattern can also be found on some heavy vehicles in which first gear is an extra-low ratio for use in extreme standing-start conditions, and would see little use in normal driving.

This is a typical shift pattern for a six-speed transmission:



Six speeds is the maximum usually seen in single range transmissions, however many semi trucks and other large commercial vehicles have manual transmissions with 8, 16 or even 20 speeds, which is made possible due to multi-range gearboxes. In such a case, Reverse is placed outside of the "H," with a canted shift path, to prevent the shift lever from intruding too far into the driver's space (in left-hand drive cars) when reverse is selected. This is the most common layout for a six-speed manual transmission.

Most front-engined, rear-wheel drive cars have a transmission that sits between the driver and the front passenger seat. Floor-mounted shifters are often connected directly to the transmission. Front-wheel drive and rear-engined cars often require a mechanical linkage to connect the shifter to the transmission.

"Four-on-the-Floor"

Historically, four-speed floor shifters were sometimes referred to as "four on the floor," during the period when steering column mounted shifters were more common. The latter, often being the standard non-performance transmission, usually had only three forward speeds and were referred to as "three on the tree."

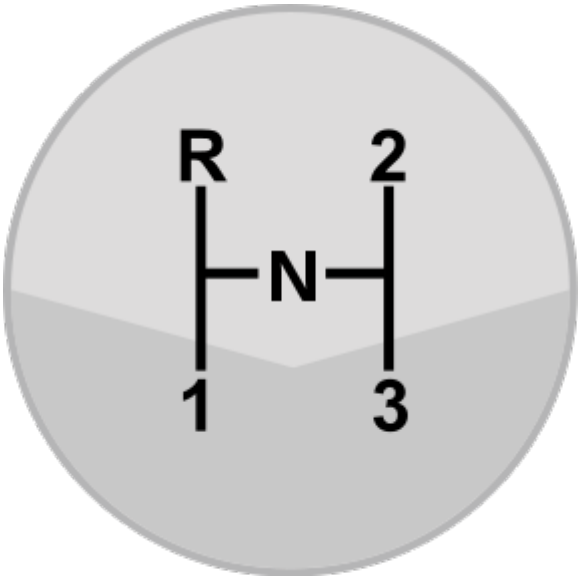
Column-mounted shifter

Column mounted gear shift lever in a Saab 96

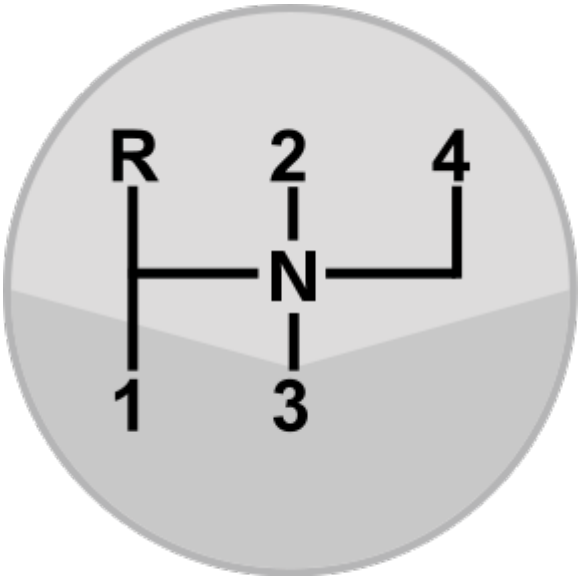
Some cars have a gear lever mounted on the steering column of the car. It was common in some countries in the past but is no longer common today. However, many automatic transmissions still use this placement.

Column shifters are mechanically similar to floor shifters, although shifting occurs in a vertical plane instead of a horizontal one. Column shifters also generally involve additional linkages to connect the shifter with the transmission. Also, the pattern is not "intuitive," as the shifter has to be moved backward and upward into R to make the car go backward. The major advantage of a column shifter is that the driver can switch between the two most commonly used gears without letting go of the steering wheel, by reaching the lever using the index and middle fingers.

A 3-speed column shifter, nicknamed "Three on the Tree" began appearing in America in the late 1930s and became common during the 1940s and '50s. Its layout is as shown below:



First gear in a 3-speed is often called "low," while third is usually called "high." There is, of course, no overdrive. Later, European and Japanese models began to have 4-speed column shifters and some of these made their way to the USA. Its layout is shown here:



However, the column manual shifter disappeared in North America by the mid 1980s, last appearing in the 1987 Chevrolet c10. But in the rest of the world, the column mounted shifter remained in production, and was in fact common in some places. For example, all Toyota Crown and Nissan Cedric taxis in Hong Kong had the 4-speed column shift until 1999 when automatic began to be offered. Since the late 1980s or early 1990s, a 5-speed column shifter has been made in some vans sold in Asia and Europe, such as Toyota Hiace and Mitsubishi L400.

Console-mounted shifter

Newer small cars and MPV's, like the Suzuki MR Wagon, the Fiat Multipla, the Toyota Matrix, the Pontiac Vibe, the Chrysler RT platform cars and the Honda Civic Si EP3 may feature a manual or automatic transmission gear shifter located on the vehicle's instrument panel. Console-mounted shifters are similar to floor-mounted gear shifters in that most of the ones used in modern cars operate on a horizontal plane and can be mounted to the vehicle's transmission in much the same way a floor-mounted shifter can. However, because of the location of the gear shifter in comparison to the locations of the column shifter and the floor shifter, as well as the positioning of the shifter to the rest of the controls on the panel often require that the gearshift be mounted in a space that does not feature a lot of controls integral to the vehicle's operation or frequently used controls, such as those for the car stereo or car air conditioning, to help prevent accidental activation or driver confusion, especially in right-hand drive cars.

More and more small cars and vans from manufacturers such as Suzuki, Honda, and Volkswagen are featuring console shifters in that they free up space on the floor for other car features such as storage compartments without requiring that the gear shift be mounted on the steering column. Also, the basic location of the gear shift in comparison to the column shifter makes console shifters easier to operate than column shifters.

Sequential manual

Some transmissions do not allow the driver to arbitrarily select any gear. Instead, the driver may only ever select the next-lowest or next-highest gear ratio. Sequential transmissions often incorporate a synchro-less dog-clutch engagement mechanism (instead of the synchromesh dog clutch common on H-pattern automotive transmissions), in which case the clutch is only necessary when selecting first or reverse gear from neutral, and most gear changes can be performed without the clutch. However, sequential shifting and synchro-less engagement are not inherently linked, though they often occur together due to the environment(s) in which these transmissions are used, such as racing cars and motorcycles.

Sequential transmissions are generally controlled by a forward-backward lever, foot pedal, or set of paddles mounted behind the steering wheel. In some cases, these are connected mechanically to the transmission. In many modern examples, these controls are attached to sensors which instruct a transmission computer to perform a shift—many of these systems can be switched into an automatic mode, where the computer controls the timing of shifts, much like an automatic transmission.

Motorcycles typically employ sequential transmissions, although the shift pattern is modified slightly for safety reasons. In a motorcycle the gears are usually shifted with the left foot pedal, the layout being this:

The gear shift lever on a 2003 Suzuki SV650S motorcycle.

6 5 ⌟ 4 ⌟ 3 ⌟ 2 ⌟ N 1

The pedal goes one step–both up and down–from the center, before it reaches its limit and has to be allowed to move back to the center position. Thus, changing multiple gears in one direction is accomplished by repeatedly pumping the pedal, either up or down. Although neutral is listed as being between first and second gears for this type of transmission, it "feels" more like first and second gear are just "further away" from each other than any other two sequential gears. Because this can lead to difficulty in finding neutral for inexperienced riders most motorcycles have a neutral indicator light on the instrument panel to help find neutral. The reason neutral does not actually have its own spot in the sequence is to make it quicker to shift from first to second when moving. Depending on the age of your motorcycle, gearbox, or skill, you can accidentally shift into neutral, although most high end, newer model motorcycles have found ways around this. The reason for having neutral between the first and second gears instead of at the bottom is that when stopped, the rider can just click down repeatedly and know that they will end up in first and not neutral. This allows a rider to quickly move his bike from a standstill in an emergency situation. This may also help on a steep hill on which high torque is required. It could be disadvantageous or even dangerous to attempt to be in first without realizing it, then try for a lower gear, only to get neutral.

On motorcycles used on race tracks, the shifting pattern is often reversed, that is, the rider clicks down to upshift. This usage pattern increases the ground clearance by placing the riders foot above the shift lever when the rider is most likely to need it, namely when leaning over and exiting a tight turn.

The shift pattern for most underbone motorcycles with an automatic centrifugal clutch is also modified for two key reasons - to enable the less-experienced riders to shift the gears without problems of "finding" neutral, and also due to the greater force needed to "lift" the gearshift lever (because the gearshift pedal of an underbone motorcycle also operates the clutch). The gearshift lever of an underbone motorcycle has two ends. The rider clicks down the front end with the left toe all the way to the top gear and clicks down the rear end with the heel all the way down to neutral. Some underbone models such as the Honda Wave and Kawasaki Fury series have a "rotary" shift pattern, which means that the rider can shift directly to neutral from the top gear, but for safety reasons this is only possible when the motorcycle is stationary. Some models also have gear position indicators for all gear positions at the instrument panel.

Semi-manual

Some new transmissions (Alfa Romeo's Selespeed gearbox and BMW's *Sequential Manual Gearbox* (SMG) for example) are conventional manual transmissions with a computerized control mechanism. These transmissions feature independently selectable gears but do not have a clutch pedal. Instead, the transmission computer controls a servo which disengages the clutch when necessary.

These transmissions vary from sequential transmissions in that they still allow nonsequential shifts: BMWs SMG system, for example, can shift from 6^{th} gear directly to 4^{th} gear.

In the case of the early second generation Saab 900, a 'Seletronic' option was available where gears were shifted with a conventional shifter, but the clutch is controlled by a computer.

Benefits and drawbacks

Benefits

Manual transmissions generally offer better fuel economy than automatic torque converter transmissions; however the disparity has been somewhat offset with the introduction of locking torque converters on automatic transmissions. Increased fuel economy with a properly operated manual transmission vehicle versus an equivalent automatic transmission vehicle can range from 5% to about 15% depending on driving conditions and style of driving. Manual transmissions do not require active cooling and generally weigh less than comparable automatics. The manual transmission couples the engine to the transmission with a rigid clutch instead of a torque converter which slips by nature. Manual transmissions also lack the parasitic power consumption of the automatic

transmission's hydraulic pump. Additionally, they require less maintenance and are easier to repair because they have fewer moving parts and are, mechanically, much simpler than automatic transmissions. When properly operated by an experienced driver, manual transmissions also tend to last longer than automatic transmissions.

Manual transmissions also generally offer a higher selection of gear ratios. Many vehicles offer a 5-speed or 6-speed manual, whereas the automatic option would typically be a 4-speed. The higher selection of gears allowed for more uses of the engine's power band, allowing for higher fuel economy and power output. This is generally due to the space available inside of a manual transmission versus an automatic since the latter requires extra components for self-shifting, such as torque converters and pumps. Automatic transmissions are now adding more speeds as the technology matures. ZF currently makes an 8-Speed automatic transmission, which is used on the Rolls Royce Ghost and the Bentley Mulsanne. The automatic transmission in the Nissan 370Z also has 7 speeds.

Manual transmissions are more efficient than conventional automatics and belt-driven continuously-variable transmissions. The driver has more direct control over the car with a manual than with an automatic, which can be employed by an experienced, knowledgeable driver who knows the correct procedure for executing a driving maneuver, and wants the vehicle to realize his or her intentions exactly and instantly. When starting forward, for example, the driver can control how much torque goes to the tires, which is useful on slippery surfaces such as ice, snow or mud. This can be done with clutch finesse, or by starting in second gear instead of first. An engine coupled with a manual transmission can often be started by the method of push starting. This is particularly useful if the starter is inoperable or defunct or the battery has drained below operable voltage. Likewise, a vehicle with a manual transmission and no clutch/starter interlock switch can be moved, if necessary, by cranking the starter while in gear. This is useful when the vehicle will not start, but must be immediately moved e.g. off the road in the event of a breakdown, if the vehicle has stalled on a railway crossing, or in extreme off-roading cases such as an engine that has stalled in deep water.

Currently only fully manual transmissions allow the driver to fully exploit the engine power at low to medium engine speeds. This is because even automatic transmissions which provide some manual mode (e.g. tiptronic), use a throttle kickdown switch, which forces a downshift on full throttle and causes the gearbox to ignore a user command to upshift on full throttle. This is especially notable on uphill roads, where cars with automatic transmission need to slow down to avoid downshifts, whereas cars with manual transmission and identical or lower engine power are still able to maintain their speed.

In contrast to most manual gearboxes, most automatic transmissions have a free-wheel-clutch. This means that the engine does not slow down the car when the driver steps off the throttle, also known as engine braking. This leads to more usage of the brakes in cars with automatic transmissions. However, the automatic gearboxes in commodity Nissans and Hondas disable the free wheel operation completely if the driver has selected a gear

position other than "D" - either "1", "2", or "D with overdrive off". This works by blocking the free-wheel sprag using a multi-disk clutch called the "overrun clutch".

Drawbacks

The smoothness and correct timing of gear shifts are wholly dependent on the driver's experience and skill. If an inexperienced driver selects the wrong gear by mistake, she/he can do damage to the engine and/or transmission.

Attempting to select reverse while the vehicle is moving forward causes severe gear wear (except in transmissions with synchromesh on the reverse gear). Most manual transmissions have a gate that locks out reverse directly from 5th gear however, to help prevent this. In order to engage reverse from 5th, the shift lever has to be moved to the center position between 2nd and 3rd, then back over and into reverse. Many newer six-speed manual transmissions have a collar under the shift knob which must be lifted to engage reverse to also help prevent this.

Choosing too low a gear with the car moving at speed can over-rev and damage the engine. There is a learning curve with a manual transmission; the driver must develop a feel for properly engaging the clutch, especially when starting forward on a steep road or when parking on an incline.

Some automatic transmissions can shift ratios faster than a manual gear change can be accomplished, due to the time required for the average driver to push the clutch pedal to the floor and move the gearstick from one position to another. This is especially true in regards to dual clutch transmissions, which are specialized computer-controlled manual transmissions. Even though some automatic transmissions and semi-automatic transmissions can shift faster, many purists still prefer a regular manual transmission.

Manual transmissions place a slightly greater workload on the driver in heavy traffic situations, when the driver must often operate the clutch pedal. In comparison, automatic transmissions merely require moving the foot from the accelerator pedal to the brake pedal, and vice versa. Manual transmissions require the driver to remove one hand periodically from the steering wheel while the vehicle is in motion.

Applications and popularity

Many types of automobiles are equipped with manual transmissions. Small economy cars predominantly feature manual transmissions because they are cheap and efficient, although many are optionally equipped with automatics. Economy cars are also often powered by very small engines, and manual transmissions make more efficient use of the power produced.

Sports cars are also often equipped with manual transmissions because they offer more direct driver involvement and better performance. Off-road vehicles and trucks often

feature manual transmissions because they allow direct gear selection and are often more rugged than their automatic counterparts.

Conversely, manual transmissions are no longer popular in many classes of cars sold in North America, Australia and Asia, although they remain dominant in Europe and developing countries. Nearly all cars are available with an automatic transmission option, and family cars and large trucks sold in the US are predominantly fitted with automatics, however in some cases if a buyer wishes he/she can have the car fitted with a manual transmission at the factory. In Europe most cars are sold with manual transmissions. Most luxury cars are only available with an automatic transmission. In most cases where both transmissions are available for a given car, automatics are an at cost option, but in some cases the reverse is true. Some cars, such as rental cars and taxis, are nearly universally equipped with automatic transmissions in countries such as the US, but the opposite is true in Europe. As of 2008, 75.2% of vehicles made in Western Europe were equipped with manual transmission, versus 16.1% with automatic and 8.7% with other.

In some places (for example Australia, New Zealand (for the second-phase Restricted licence, but not the final Full licence), Belgium, China, Estonia, Dominican Republic, Finland, France, Germany, Ireland, Israel, Netherlands, Norway, Poland, Singapore, Slovenia, South Africa, South Korea, Spain, Sri Lanka, Sweden, Turkey, U.A.E and the UK), when a driver takes the licensing road test using an automatic transmission, the resulting license is restricted to the use of automatic transmissions. This treatment of the manual transmission skill seems to maintain the widespread use of the manual transmission. As many new drivers worry that their restricted license will become an obstacle for them where most cars have manual transmissions, they make the effort to learn with manual transmissions and obtain full licenses. Some other countries (such as India, Pakistan, Malaysia, Serbia, Brazil, and Denmark) go even further, whereby the license is granted only when a test is passed on a manual transmission. In Denmark and Brazil you are allowed to take the test on an automatic if you are handicapped, with such license you will not be able to drive a manual transmission.

Truck transmissions

Some trucks have transmissions that look and behave like ordinary car transmissions - these transmissions are used on lighter trucks, typically have up to 6 gears, and usually have synchromesh.

For trucks needing more gears, the standard "H" pattern can get very complicated, so additional controls are used to select additional gears. The "H" pattern is retained, then an additional control selects among alternatives. In older trucks, the control is often a separate lever mounted on the floor or more recently a pneumatic switch mounted on the "H" lever; in newer trucks the control is often an electrical switch mounted on the "H" lever. Multi-control transmissions are built in much higher power ratings, but rarely use synchromesh.

There are several common alternatives for the shifting pattern. Usual types are:

- **Range transmissions** use an "H" pattern through a narrow range of gears, then a "range" control shifts the "H" pattern between high and low ranges. For example, an 8-speed range transmission has an H shift pattern with four gears. The first through fourth gears are accessed when low range is selected. To access the fifth through eighth gears, the range selector is moved to high range, and the gear lever again shifted through the first through fourth gear positions. In high range, the first gear position becomes fifth, the second gear position becomes sixth, and so on.
- **Splitter transmissions** use an "H" pattern with a wide range of gears, and the other selector splits each sequential gear position in two: First gear is in first position/low split, second gear is in first position/high split, third gear is in second position/low split, fourth gear is in second position/high split, and so on.
- **Range-Splitter transmissions** combine range-splitting and gear-splitting. This allows even more gear ratios. Both a range selector and a splitter selector are provided.

Although there are many gear positions, shifting through gears usually follows a regular pattern. For example, a series of upshifts might use "move to splitter direct; move to splitter overdrive; move shift lever to #2 and move splitter to underdrive; move splitter to direct; move splitter to overdrive; move shift lever to #3 and move splitter to underdrive"; and so on. In older trucks using floor-mounted levers, a bigger problem is common gear shifts require the drivers to move their hands between shift levers in a single shift, and without synchromesh, shifts must be carefully timed or the transmission will not engage. For this reason, some splitter transmissions have an additional "under under" range, so when the splitter is already in "under" it can be quickly downshifted again, without the delay of a double shift.

Today's truck transmissions are most commonly "range-splitter". The most common 13 speed has a standard H pattern, and the pattern from left upper corner is as follows: R, down to L, over and up to 1, down to 2, up and over to 3, down to 4. The "butterfly" range lever in the center front of the knob is flipped up to high range while in 4th, then shifted back to 1. The 1 through 4 positions of the knob are repeated. Also, each can be split using the thumb-actuated under-overdrive lever on the left side of the knob while in high range. The "thumb" lever is not available in low range, except in 18 speeds; 1 through 4 in low range can be split using the thumb lever and L can be split with the "Butterfly" lever. L cannot be split using the thumb lever in either the 13 or 18 speed. The 9 speed transmission is basically a 13 speed without the under-overdrive thumb lever.

Truck transmissions use many physical layouts. For example, the output of an N-speed transmission may drive an M-speed secondary transmission, giving a total of N*M gear combinations; for example a 4-speed main box and 3-speed splitter gives 12 ratios. Transmissions may be in separate cases with a shaft in between; in separate cases bolted together; or all in one case, using the same lubricating oil. The second transmission is often called a "Brownie" or "Brownie box" after a popular brand. With a third transmission, gears are multiplied yet again, giving greater range or closer spacing. Some

trucks thus have dozens of gear positions, although most are duplicates. Sometimes a secondary transmission is integrated with the differential in the rear axle, called a "two-speed rear end." Two-speed differentials are always splitters. In newer transmissions, there may be two countershafts, so each main shaft gear can be driven from one or the other countershaft; this allows construction with short and robust countershafts, while still allowing many gear combinations inside a single gear case.

Heavy-duty transmissions are almost always non-synchromesh. One argument is synchromesh adds weight that could be payload, is one more thing to fail, and drivers spend thousands of hours driving so can take the time to learn to drive efficiently with a non-synchromesh transmission. Heavy-duty trucks driven frequently in city traffic, such as cement mixers, need to be shifted very often and in stop-and-go traffic. Since few heavy-duty transmissions have synchromesh, automatic transmissions are commonly used instead, despite their increased weight, cost, and loss of efficiency.

Heavy trucks are usually powered with diesel engines. Diesel truck engines from the 1970s and earlier tend to have a narrow power band, so need many close-spaced gears. Starting with the 1968 Maxidyne, diesel truck engines have increasingly used turbochargers and electronic controls that widen the power band, allowing fewer and fewer gear ratios. A transmission with fewer ratios is lighter and may be more efficient due to fewer transmissions in series. Fewer shifts also makes the truck more drivable. As of 2005, fleet operators often use 9,10,13 or 18-speed transmissions, but automated manual and semi-automatic transmissions are becoming more common on heavy vehicles, as they can improve efficiency and drivability, reduce the barrier to entry for new drivers, and may improve safety by allowing the driver to concentrate on road conditions.

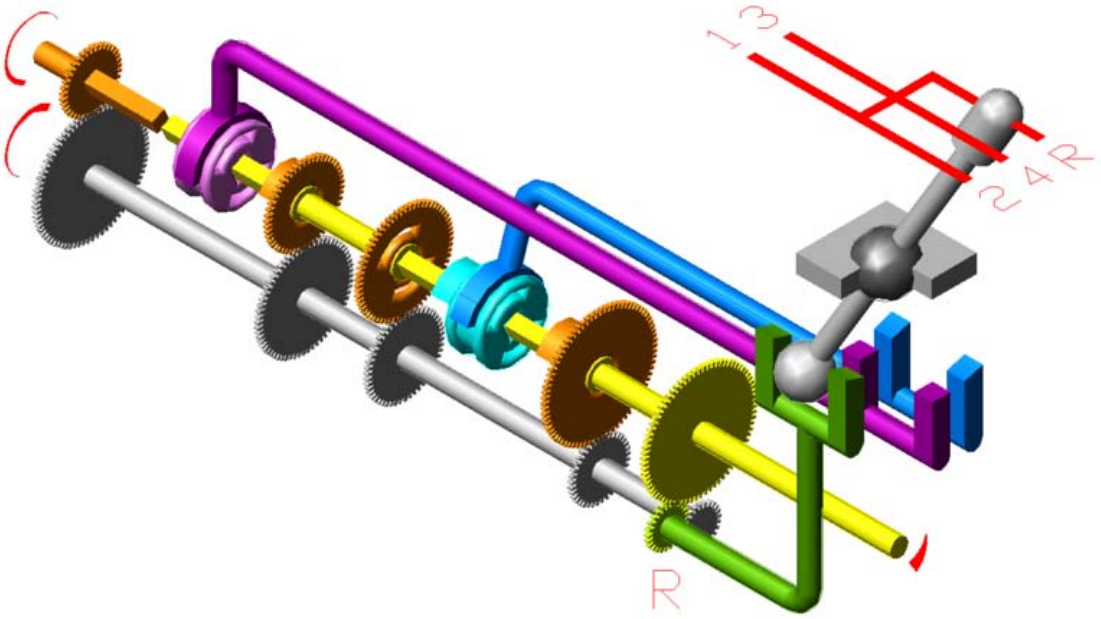
Maintenance

Because clutches use changes in friction to modulate the transfer of torque between engine and transmission, they are subject to wear in everyday use. A very good clutch, when used by an expert driver, can last hundreds of thousands of kilometres (or miles). Weak clutches, abrupt downshifting, inexperienced drivers, and aggressive driving can lead to more frequent repair or replacement.

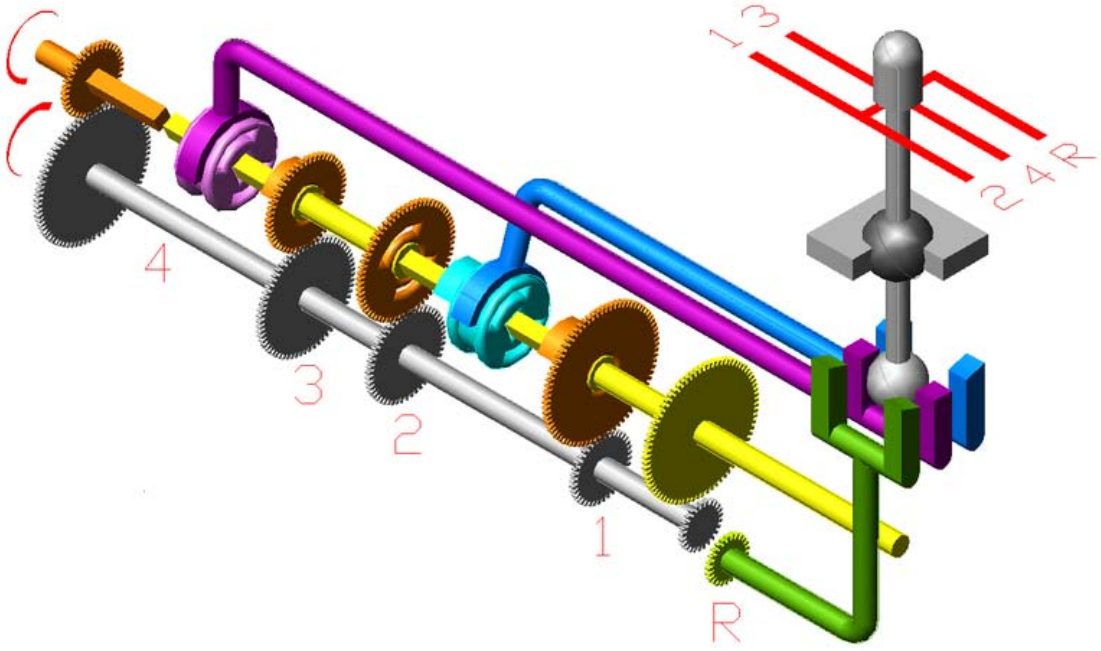
Manual transmissions are lubricated with gear oil or engine oil in some cars, which must be changed periodically in some cars, although not as frequently as the automatic transmission fluid in a vehicle so equipped. (Some manufacturers specify that changing the gear oil is never necessary except after transmission work or to rectify a leak.)

Gear oil has a characteristic aroma due to the addition of sulfur-bearing anti-wear compounds. These compounds are used to reduce the high sliding friction by the helical gear cut of the teeth (this cut eliminates the characteristic whine of straight cut spur gears). On motorcycles with "wet" clutches (clutch is bathed in engine oil), there is usually nothing separating the lower part of the engine from the transmission, so the same

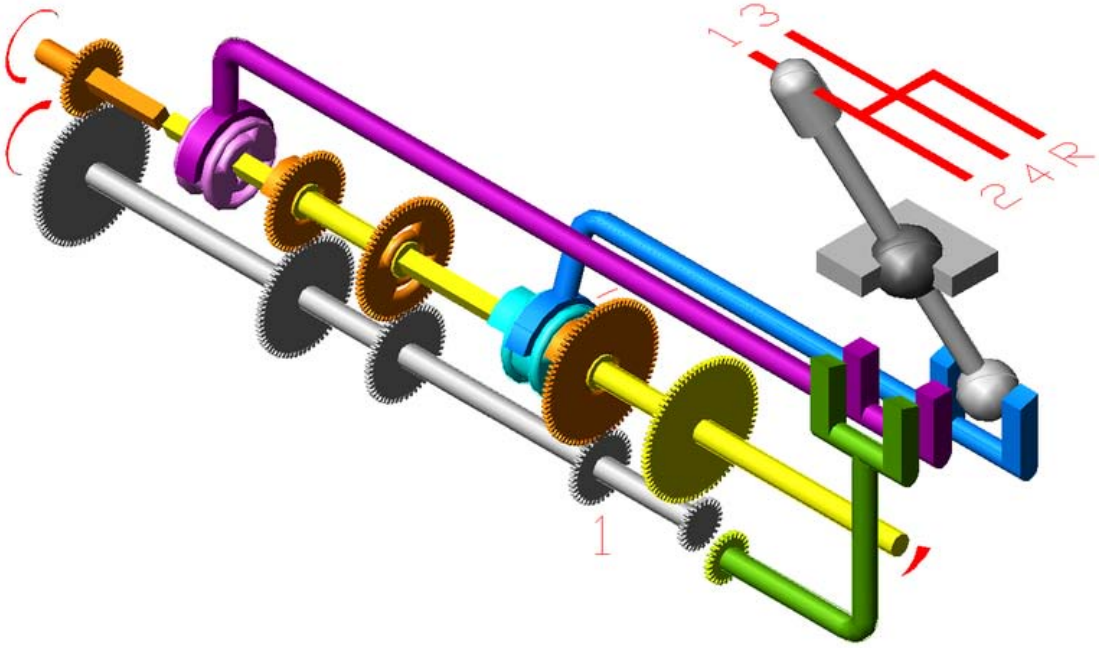
oil lubricates both the engine and transmission. The original Mini placed the gearbox in the oil sump below the engine, thus using the same oil for both.



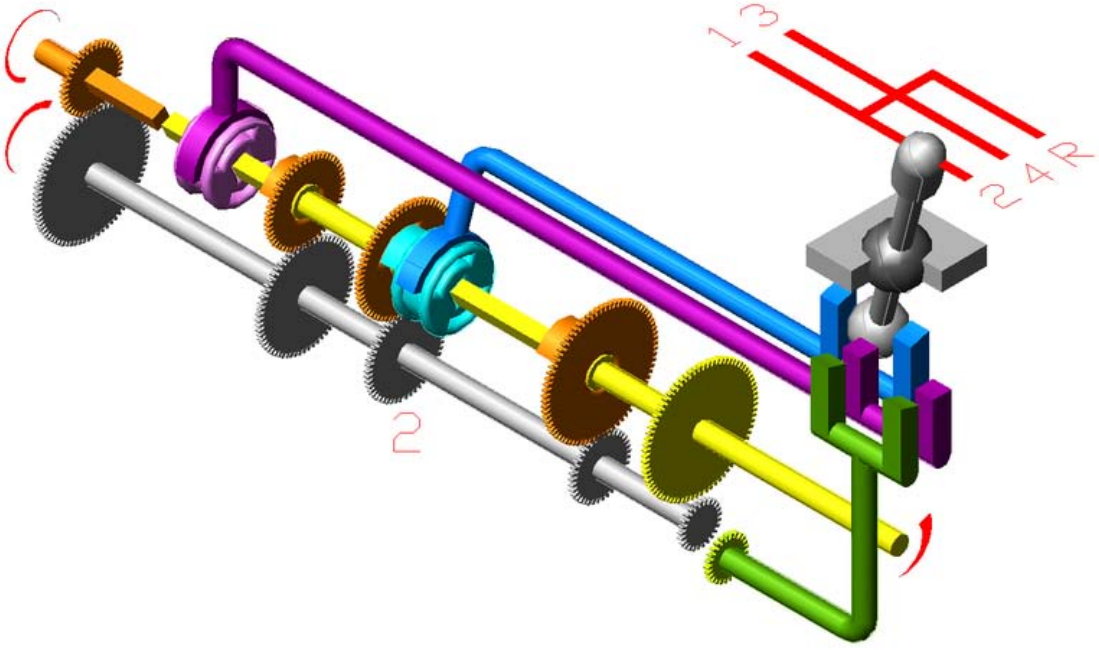
Reverse



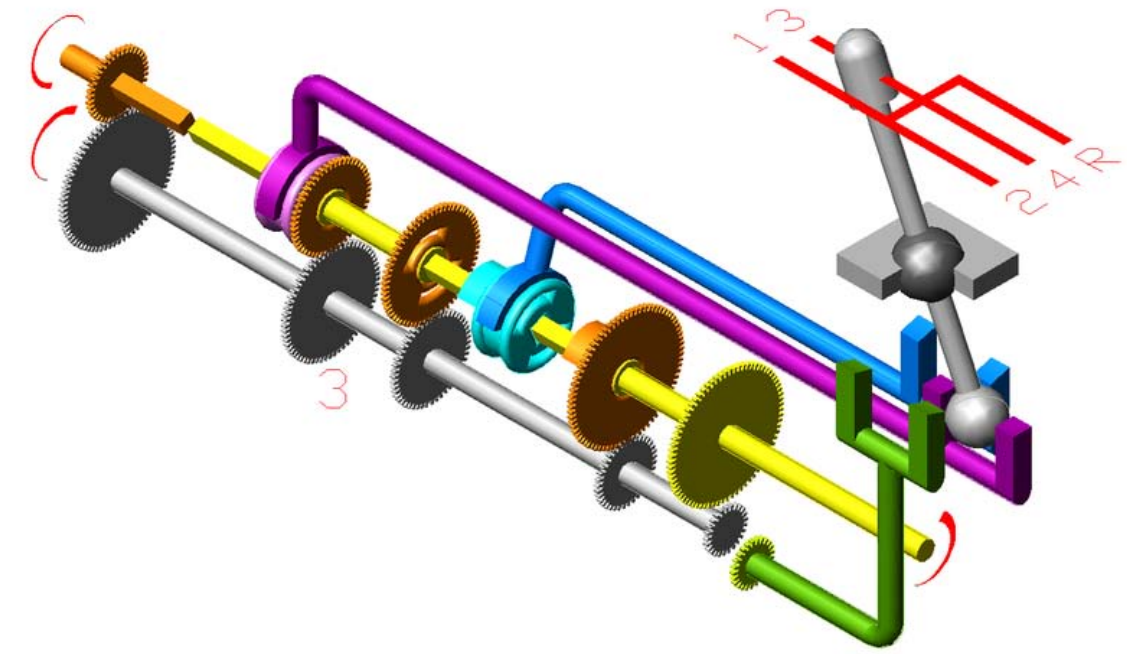
Neutral



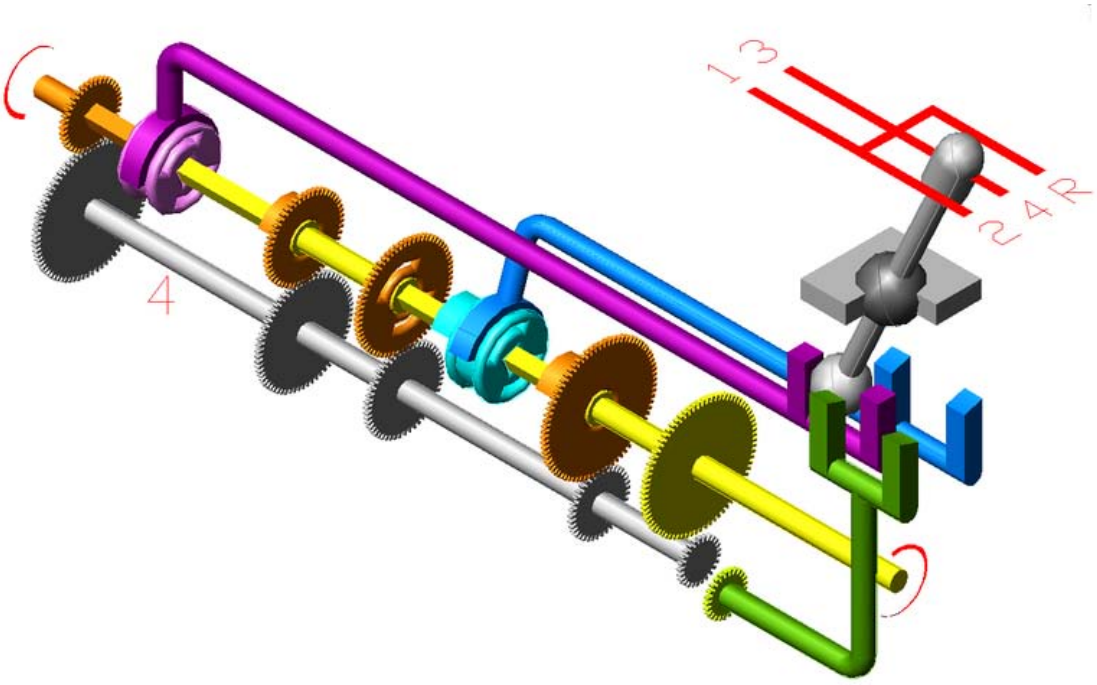
First gear



Second gear



Third gear



Fourth gear

Chapter 3

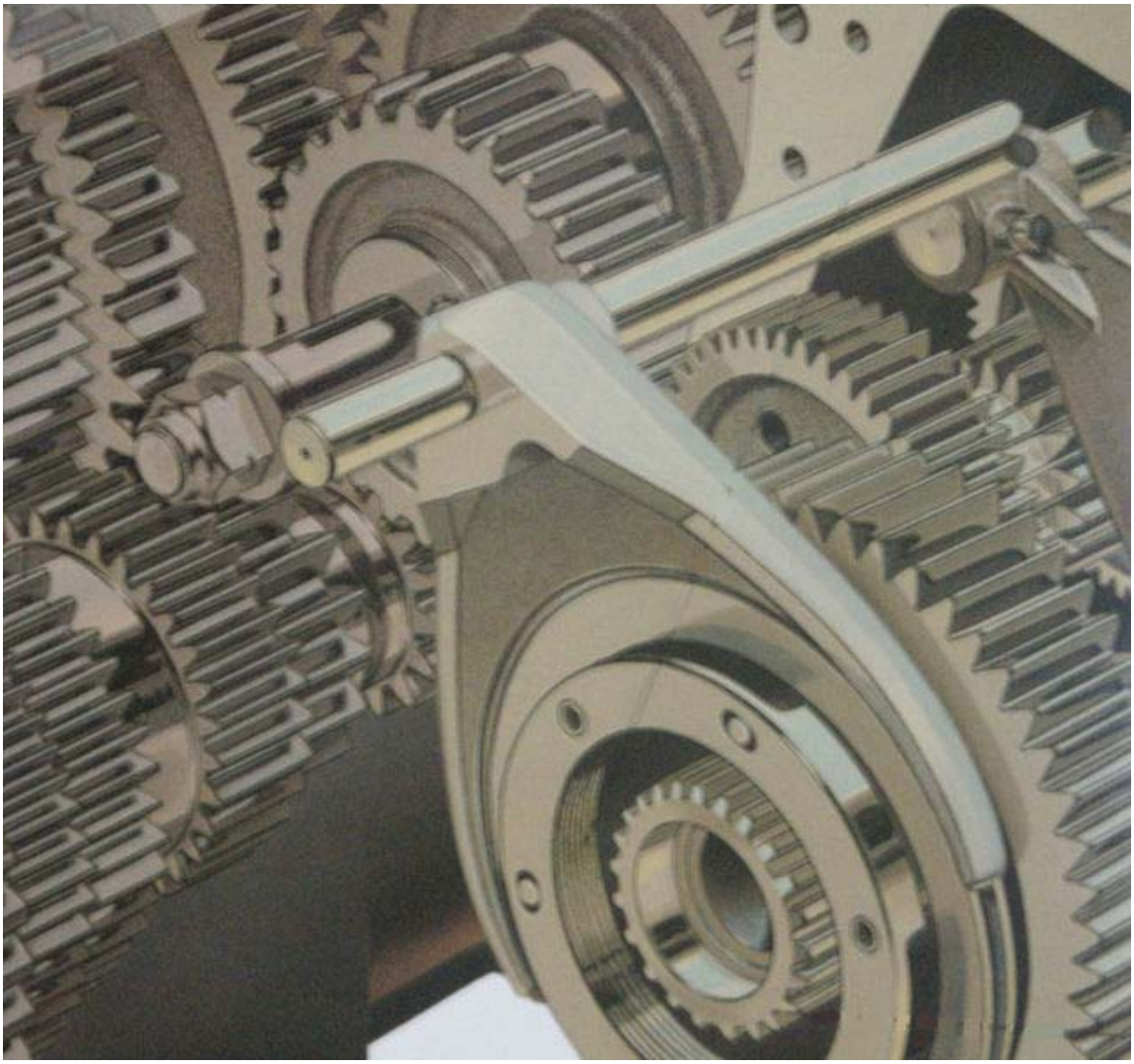
Non-Synchronous Transmission

A **non-synchronous transmission** is a form of transmission based on gears that do not use synchronizing mechanisms. They are found primarily in various types of agricultural, and commercial vehicles. Because the gear boxes are engineered without "cone and collar" synchronizing technology, the non-synchronous transmission type requires an understanding of gear range, torque, engine power, range selector, multi-functional clutch, and shifter functions. Engineered to pull tremendous loads, often equal to or exceeding 40 tons, some vehicles may also use a combination of transmissions for different mechanisms. An example would be a PTO.

History

In 1842, the reversing lever was invented and patented as the Walschaerts valve gear in Belgium, and reversing lever descriptions exists in British, and American mechanic's diagrams. In 1890, Panhard used a chain-drive with a Daimler engine in a horseless carriage. Industrial marketing has since then coined spectacular names for various vehicle parts. Changing from the Locomobile, a 1906 race-car to what is now called the automobile, advertisers used design wording from the engineering departments to give new ideas a desirable appeal for sales promotions. From 1932, synchronizer mechanisms began to appear in automotive transmissions. The split off of automotive transmission types that has prevailed in engineering designs uses three major categories: *automatic*, *manual*, and *non-synchronous*. Some of the differences are improvements, including the continuously variable transmission installed in hybrid vehicles that are powered partly by an internal combustion engine, and partly by an electric motor. The concepts of transmission continue to employ methods for transferring the most conceivably efficient use of power.

How non-synchronization works



Non-synchronous transmissions are engineered with the understanding that a trained operator will be shifting gears in a known coordination of timing. Commercial vehicle operators use a double-clutching technique that is taught in driver's trade schools. The most skillful drivers can shift these transmissions without using the clutch by bringing the engine to exactly the right rpm in neutral before attempting to complete a shift, a technique called "float-shifting." With payloads of cargo ranging in commercial freight of 80,000 lbs (40 tons (short) or 36.3 tonnes) or more, some heavy haulers have over 24 gears that an operator will shift through before reaching a top cruising speed of 70 mph. Many low-low (creeper) gears are used in farm equipment to plow, till, or harvest. An inexperienced operator would suddenly find a piece of heavy equipment stuck in gear under full power, or even worse unable to shift into gear a runaway vehicle in neutral headed down a steep slope, unless he understood the synchronizing skill, and torque issues in non-synchronous transmissions. Many mountain roads require heavy equipment operators to remain in gear and not shift while passing down a steep grade. For more details about steep grade operation see either jake brake, or engine brake. Many other

circumstances face operators of non-synchronous transmissions. Safety and operator skills need to be learned before operating any of these types of vehicles.

Double clutching (commercial motor vehicle)

Operators of 18-wheelers, farm equipment, tractors and other heavy equipment learn to float the transmission in and out of gear, beginning with dis-engaging the clutch by pressing the clutch pedal *only part way, enough* to pull the transmission out of gear, re-engaging the clutch in neutral (between gears by letting the clutch pedal all the way back out) to let the engine revolutions decelerate enough for the idle sprockets to shift, and free gear shafts to slow their revolutions per minute (RPM), then dis-engage the clutch again (by pressing the clutch pedal *only part way to the floor*) a 2nd time, and float the higher gear into engaging the drive coupling and fly wheel and engaging the clutch plates.

Professional operators of heavy equipment take extensive safety training before ever learning how to double-clutch. Once an operator is familiar with range, range selector, rpm, velocity, and torque of heavy equipment like an 18-wheeler, they can begin to anticipate when to shift gears. Operators become familiar with ranges of gears. They also learn not to leave their foot on the clutch while driving, because these types of transmissions use the clutch for several very different purposes. The depth the clutch is depressed to the floor will determine what the clutch will be doing as a synchronizing function.

Clutch brake

Unlike any other type of transmission, non-synchronous transmissions often have a mechanism for slowing down, or stopping an idle gear. In commercial motor vehicles, this mechanism is called the *clutch brake*, and is used by depressing the clutch all the way to the floor. This is useful in 18-wheelers that have just started their diesel engines, and are releasing parking locks, and engaging the transmission from a stop. The clutch brake not only slows or stops the idle gear axis, but can also prevent shifting into gear until the clutch is lifted a few inches off the floor. In order to shift into gear, the clutch must be half way off the floor, otherwise the clutch brake will prevent the transmission from being shifted into or out of gear. Mechanics must often repair or replace the *clutch brake* in a non-synchronous transmission when an inexperienced operator wears it out, it becomes inoperable, or has lost its function.

Comparison of transmissions

Non-synchronous transmissions are designed to depend upon an operator experienced in changing gears. These types of transmissions are known to heavy equipment operators as non-synchronous transmissions. The operators must understand how to shift these transmissions into and out of gear. Many learn how to do this in certifying schools.

All *automatic transmissions* have synchronizing mechanisms. Most manual transmissions also have synchronizers. But, there are still other types of transmissions used mostly in commercial applications that are non-synchronous.

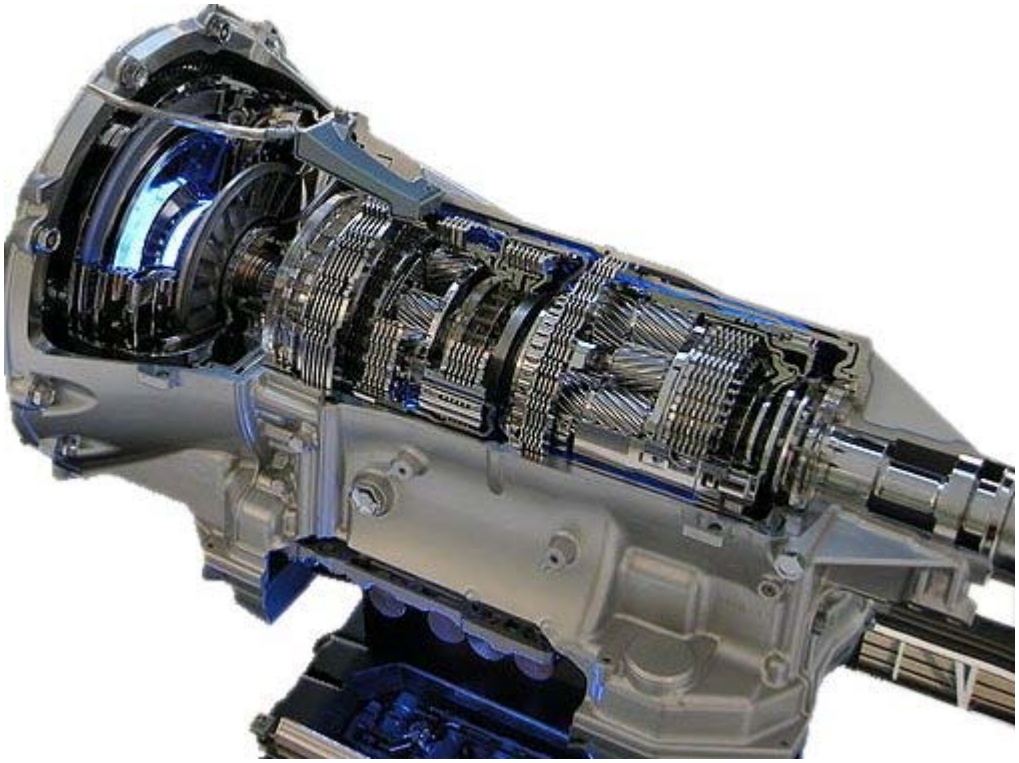
Fully synchronous,hydrau-pneumatic systems are designed to change gears based on engine performance, and other velocity indicators, delivering torque to drive wheels. These transmissions have synchronizing mechanisms (called cone & collar synchronizers) that are designed to keep gear dog-teeth from being broken off.

Heavy equipment for industrial, military, or farm use have different torque and load issues. They have unique stress from massive horsepower that would make converter faces shear. For the reasons of engineering a dependable, longer-life piece of equipment, these machines often use non-synchronous transmissions.

Any transmission that requires the operator to manually synchronize engine crank-shaft revolutions (RPM) with drive-shaft revolutions is non-synchronous.

Chapter 4

Automatic Transmission



An 8-gear automatic transmission

An **automatic gearbox** is one type of motor vehicle transmission that can automatically change gear ratios as the vehicle moves, freeing the driver from having to shift gears manually. Most automatic transmissions have a defined set of gear ranges, often with a parking pawl feature that locks the output shaft of the transmission.

Similar but larger devices are also used for heavy-duty commercial and industrial vehicles and equipment. Some machines with limited speed ranges or fixed engine speeds, such as some forklifts and lawn mowers, only use a torque converter to provide a variable gearing of the engine to the wheels.

Besides automatics, there are also other types of automated transmissions such as continuous variable transmissions (CVTs) and semi-automatic transmissions, that free the driver from having to shift gears manually, by using the transmission's computer to change gear, if for example the driver were redlining the engine. Despite superficial similarity to other automated transmissions, automatic transmissions differ significantly in internal operation and driver's "feel" from semi-automatics and CVTs. An automatic uses a torque converter instead of clutch to manage the connection between the transmission gearing and the engine. In contrast, a CVT uses a belt or other torque transmission schema to allow an "infinite" number of gear ratios instead of a fixed number of gear ratios. A semi-automatic retains a clutch like a manual transmission, but controls the clutch through electrohydraulic means.

A conventional manual transmission is frequently the base equipment in a car, with the option being an automated transmission such as a conventional automatic, semi-automatic, or CVT. The ability to shift gears manually, often via paddle shifters, can also be found on certain automated transmissions (manumatics such as Tiptronic), semi-automatics (BMW SMG), and continuous variable transmissions (CVTs) (such as Lineartronic).

Comparison with manual transmission

Most cars sold in North America since the 1950s have been available with an automatic transmission. Conversely, automatic transmission is less popular in Europe, with 80% of drivers opting for manual transmission.. In most Asian markets and in Australia, automatic transmissions have become very popular since the 1990s.

Vehicles equipped with automatic transmissions are less complex to drive. Consequently, in some jurisdictions, drivers who have passed their driving test in a vehicle with an automatic transmission will not be licensed to drive a manual transmission vehicle. Examples of driving license restrictions are Croatia, Dominican Republic, Israel, United Kingdom, some states in Australia, France, Portugal, Latvia, Lebanon, Lithuania, Ireland, Belgium, Germany, Pakistan, the Netherlands, Sweden, Austria, Norway, Poland, Hungary, South Africa, Trinidad and Tobago, China, Hong Kong, Macau, Mauritius, South Korea, Romania, Singapore, Philippines, United Arab Emirates, India, Estonia, Finland, Switzerland, Slovenia, Republic of Ireland and New Zealand (Restricted licence only).

Automatic transmission modes

Conventionally, in order to select the transmission operating 'mode', the driver moves a selection lever located either on the steering column or on the floor (as with a manual). In order to select modes, or to manually select specific gear ratios, the driver must push a button in (called the shift lock button) or pull the handle (only on column mounted shifters) out. Some vehicles position selector buttons for each mode on the cockpit instead, freeing up space on the central console. Vehicles conforming to US Government standards must have the modes ordered P-R-N-D-L (left to right, top to bottom, or

clockwise). Prior to this, quadrant-selected automatic transmissions often used a P-N-D-L-R layout, or similar. Such a pattern led to a number of deaths and injuries owing to unintentional gear selection, as well as the danger of having a selector (when worn) jump into Reverse from Low gear during engine braking maneuvers.

Automatic transmissions have various modes depending on the model and make of the transmission. Some of the common modes include

Park (P)

This selection mechanically locks the output shaft of transmission, restricting the vehicle from moving in any direction. A parking pawl prevents the transmission from rotating, and therefore the vehicle from moving, although the vehicle's non-driven roadwheels may still rotate freely. For this reason, it is recommended to use the hand brake (or parking brake) because this actually locks (in most cases) the rear wheels and prevents them from moving. This also increases the life of the transmission and the park pin mechanism, because parking on an incline with the transmission in park without the parking brake engaged will cause undue stress on the parking pin. An efficiently-adjusted hand brake should also prevent the car from moving if a worn selector accidentally drops into reverse gear during early morning fast-idle engine warm-ups. It should be noted that locking the transmission output shaft does not positively lock the driving wheels. If one driving wheel slips while the transmission is in "park," the other will roll freely as the slipping wheel rotates in the opposite direction. Only a (properly adjusted) parking brake can be relied upon to positively lock both of the parking-braked wheels. (This is not the case with certain 1950's Chrysler products that carried their parking brake on the transmission tailshaft, a defect compounded by the provision of a bumper jack). It is typical of front-wheel-drive vehicles for the parking brake to be on the rear (non-driving) wheels, so use of both the parking brake and the transmission park lock provides the greatest security against unintended movement on slopes. Unfortunately, the rear of most front-wheel-drive vehicles has only about half the weight on the rear wheel as is on the front wheels, greatly reducing the security provided by the parking brake as compared to either rear-wheel-drive vehicles with parking brake on the rear wheels (which generally have near half of the total vehicle weight on the rear wheels, except for empty pickup and open-bed trucks) or to front-wheel-drive vehicles with the parking brake on the front wheels, which generally have about two-thirds of the vehicle's weight (unloaded) on the front wheels.

A car should be allowed to come to a complete stop before setting the transmission into park to prevent damage. Usually, Park (P) is one of only two selections in which the car's engine can be started, the other being Neutral (N). In many modern cars and trucks, the driver must have the foot brake applied before the transmission can be taken out of park. The Park position is omitted on buses/coaches with automatic transmission (on which a parking pawl is not practical), which must be placed in neutral with the parking brakes set. Advice is given in some owner's manuals [example: 1997 Oldsmobile Cutlass Supreme owner's manual] that if the vehicle is parked on a steep slope using the park lock

only, it may not be possible to release the park lock (move the selector lever out of "P"). Another vehicle may be required to push the stuck vehicle uphill slightly to remove the loading on the park lock pawl.

Most automobiles require **P** or **N** to be set on the selector lever before the internal combustion engine can be started. This is typically achieved via a normally open 'inhibitor' switch, which is wired in series with the starter motor engagement circuit, and is only closed when P or N is selected, thus completing the circuit (when the key is turned to the start position)

Reverse (R)

This engages reverse gear within the transmission, giving the ability for the vehicle to drive backwards. In order for the driver to select reverse in modern transmissions, they must come to a complete stop, push the shift lock button in (or pull the shift lever forward in the case of a column shifter) and select reverse. Not coming to a complete stop can cause severe damage to the transmission. Many modern automatic transmissions have a safety mechanism in place, which does to some extent prevent (but does not completely avoid) inadvertently putting the car in reverse when the vehicle is moving forwards. This mechanism usually consists of a solenoid-controlled physical barrier on either side of the Reverse position, which is electronically engaged by a switch on the brake pedal. Therefore, the brake pedal needs to be depressed in order to allow the selection of reverse. Some electronic transmissions prevent or delay engagement of reverse gear altogether while the car is moving.

Some shifters with a shift button allow the driver to freely move the shifter from R to N or D, or simply moving the shifter to N or D without actually depressing the button. However, the driver cannot put back the shifter to R without depressing the shift button to prevent accidental shifting, especially at high speeds, which could damage the transmission.

Neutral/No gear (N)

This disengages all gear trains within the transmission, effectively disconnecting the transmission from the driven roadwheels, so the vehicle is able to move freely under its own weight and gain momentum without the motive force from the engine (engine braking). This is the only other selection in which the vehicle's engine can be started.

Drive (D)

This position allows the transmission to engage the full range of available forward gear trains, and therefore allows the vehicle to move forward and accelerate through its range of gears. The number of gear 'ratios' a transmission has depends on the model, but they initially ranged from three (predominant before the 1990s), to four and five speeds (losing popularity to six-speed autos, though still favored by Chrysler and Honda/Acura). Six-speed automatic transmissions are now probably the most common offering Toyota Camry V6 models, the Chevrolet Malibu LTZ, Corvette, GM trucks, Pontiac G8, Ford Falcon BF 2005-2007 and Falcon FG 2008 - current in Australia with 6 speed ZF, and most newer model Ford/Lincoln/Mercury vehicles). However, seven-speed autos are becoming available (found in Mercedes 7G gearbox), as are eight-speed autos in the newer models of Lexus and BMW cars.

OverDrive (D, OD, or a boxed [D])
: This mode is used in some transmissions to allow early computer-controlled transmissions to engage the Automatic Overdrive. In these transmissions, Drive (D) locks the Automatic Overdrive off, but is identical otherwise. OD (Overdrive) in these cars is engaged under steady speeds or low acceleration at approximately 35–45 mph (56–72 km/h). Under hard acceleration or below 35–45 mph (56–72 km/h), the transmission will automatically downshift. Vehicles with this option should be driven in this mode unless circumstances require a lower gear.

Third (3)
: This mode limits the transmission to the first three gear ratios, or sometimes locks the transmission in third gear. This can be used to climb or going down hill. Some vehicles will automatically shift up out of third gear in this mode if a certain RPM range is reached in order to prevent engine damage. This gear is also recommended while towing a caravan.

Second (2 or S)
: This mode limits the transmission to the first two gear ratios, or locks the transmission in second gear on Ford, Kia, and Honda models. This can be used to drive in adverse conditions such as snow and ice, as well as climbing or going down hills in the winter time. Some vehicles will automatically shift up out of second gear in this mode if a certain RPM range is reached in order to prevent engine damage.
: Although traditionally considered second gear, there are other names used. Chrysler models with a three-speed automatic since the late 1980s have called this gear **3** while using the traditional names for *Drive* and *Low*.

First (1 or L [Low])
: This mode locks the transmission in first gear only. It will not change to any other gear range. This, like second, can be used during the winter season, or for towing.

As well as the above modes there are also other modes, dependent on the manufacturer and model. Some examples include

D5
: In Hondas and Acuras equipped with five-speed automatic transmissions, this mode is used commonly for highway use (as stated in the manual), and uses all five forward gears.

D4
: This mode is also found in Honda and Acura four- or five-speed automatics, and only uses the first four gear ratios. According to the manual, it is used for "stop and go traffic", such as city driving.

D3 or 3
: This mode is found in Honda, Acura, Volkswagen and Pontiac four-speed automatics and only uses the first three gear ratios. According to the manual, it is used for "stop & go traffic", such as city driving.

S or Sport
: This is commonly described as 'Sport mode'. It operates in an identical manner as 'D' mode, except that the upshifts change much higher up the engine's rev range.

This has the effect on maximising all the available engine output, and therefore enhances the performance of the vehicle, particularly during acceleration. This mode will also downchange much higher up the rev range compared to 'D' mode, maximising the effects of engine braking. This mode will have a detrimental effect on fuel economy. Hyundai has a Norm/Power switch next to the gearshift for this purpose on the Tiburon.

Some early GM's equipped with Tourqueflite transmsissons used (S) to indicate Second gear, being the same as the 2 position on a Chrysler, shifting between only first and second gears. This would have been recommended for use on steep grades, or slippery roads like dirt, or ice, and limited to speeds under 40 mph. (L) was used in some early GM's to indicate (L)ow gear, being the same as the 2 position on a Chrysler, locking the transmission into first gear. This would have been recommended for use on steep grades, or slippery roads like dirt, or ice, and limited to speeds under 15 mph.

+ −, and M
: This is for the 'manual mode' selection of gears in certain automatics, such as Porsche's Tiptronic. The M feature can also be found in Chrysler and General Motors products such as the Dodge Magnum and Pontiac G6, as well as Toyota's Camry, Corolla, Fortuner, Previa and Innova. Mitsubishi and some Audi models (TT), meanwhile do not have the M, and instead have the + and -, which is separated from the rest of the shift modes; the same is true for some Peugeot products like Peugeot 206. Meanwhile, the driver can shift up and down at will by toggling the (console mounted) shift lever like a semi-automatic transmission. This mode may be engaged either through a selector/position or by actually changing the gears (e.g., tipping the gear-down paddles mounted near the driver's fingers on the steering wheel).

Winter (W)
: In some Mercedes-Benz, BMW and General Motors Europe models, a 'Winter mode' can be engaged so that second gear is selected instead of first when pulling away from stationary, to reduce the likelihood of loss of traction due to wheelspin on snow or ice. On GM cars, this was D2 in the 1950s, and is Second Gear Start after 1990. On Ford, Kia, and Honda automatics, this feature can be accessed by moving the gear selector to 2 to start, then taking your foot off the accelerator while selecting D once the car is moving.

Brake (B)
: A mode selectable on some Toyota models. In non-hybrid cars, this mode lets the engine do compression braking, also known as engine braking, typically when encountering a steep downhill. Instead of engaging the brakes, the engine in a non-hybrid car switches to a lower gear and slows down the spinning tires. The engine holds the car back, instead of the brakes slowing it down. For hybrid cars, this mode converts the electric motor into a generator for the battery. It is not the same as downshifting in a non-hybrid car, but it has the same effect in slowing the car without using the brakes. GM called this HR (hill retarder) and GR (grade retarder) in the 1950s.

Hydraulic automatic transmissions

The predominant form of automatic transmission is hydraulically operated; using a fluid coupling or torque converter, and a set of planetary gearsets to provide a range of gear ratios.

Parts and operation

A cut-away model of a torque converter

A hydraulic automatic transmission consists of the following parts:

- *Torque converter*: A type of fluid coupling, hydraulically connecting the engine to the transmission. It takes the place of a mechanical clutch, allowing the transmission to stay 'in gear' and the engine to remain running while the vehicle is stationary, without stalling. A torque converter differs from a fluid coupling, in that it provides a variable amount of torque multiplication at low engine speeds, increasing "breakaway" acceleration. This is accomplished with a third member in the "coupling assembly" known as the stator, and by altering the shapes of the vanes inside the coupling in such a way as to curve the fluid's path into the stator. The stator captures the kinetic energy of the transmission fluid, in effect using the leftover force of it to enhance torque multiplication.
- *Pump*, not to be confused with the impeller inside the torque converter, is typically a gear pump mounted between the torque converter and the planetary gearset. It draws transmission fluid from a sump and pressurizes it, which is

needed for transmission components to operate. The input for the pump is connected to the torque converter housing, which in turn is bolted to the engine's flywheel, so the pump provides pressure whenever the engine is running and there is enough transmission fluid.

- *Planetary gearset*: A compound epicyclic planetary gearset, whose bands and clutches are actuated by hydraulic servos controlled by the valve body, providing two or more gear ratios.
- *Clutches and bands:* to effect gear changes, one of two types of clutches or bands are used to hold a particular member of the planetary gearset motionless, while allowing another member to rotate, thereby transmitting torque and producing gear reductions or overdrive ratios. These clutches are actuated by the valve body (see below), their sequence controlled by the transmission's internal programming. Principally, a type of device known as a sprag or roller clutch is used for routine upshifts/downshifts. Operating much as a ratchet, it transmits torque only in one direction, free-wheeling or "overrunning" in the other. The advantage of this type of clutch is that it eliminates the sensitivity of timing a simultaneous clutch release/apply on two planetaries, simply "taking up" the drivetrain load when actuated, and releasing automatically when the next gear's sprag clutch assumes the torque transfer. The bands come into play for manually selected gears, such as low range or reverse, and operate on the planetary drum's circumference. Bands are not applied when drive/overdrive range is selected, the torque being transmitted by the sprag clutches instead. Bands are used for braking; the GM Turbo-Hydramatics incorporated this..
- *Valve body*: hydraulic control center that receives pressurized fluid from the *main pump* operated by the fluid coupling/torque converter. The pressure coming from this pump is regulated and used to run a network of spring-loaded valves, check balls and servo pistons. The valves use the pump pressure and the pressure from a centrifugal governor on the output side (as well as hydraulic signals from the range selector valves and the *throttle valve* or *modulator*) to control which ratio is selected on the gearset; as the vehicle and engine change speed, the difference between the pressures changes, causing different sets of valves to open and close. The hydraulic pressure controlled by these valves drives the various clutch and brake band actuators, thereby controlling the operation of the planetary gearset to select the optimum gear ratio for the current operating conditions. However, in many modern automatic transmissions, the valves are controlled by electro-mechanical servos which are controlled by the electronic engine control unit (ECU) or a separate transmission control unit (TCU).
- *Hydraulic & lubricating oil*: called automatic transmission fluid (ATF), this component of the transmission provides lubrication, corrosion prevention, and a hydraulic medium to convey mechanical power (for the operation of the transmission). Primarily made from refined petroleum, and processed to provide properties that promote smooth power transmission and increase service life, the ATF is one of the few parts of the automatic transmission that needs routine service as the vehicle ages.

The multitude of parts, along with the complex design of the valve body, originally made hydraulic automatic transmissions much more complicated (and expensive) to build and repair than manual transmissions. In most cars (except US family, luxury, sport-utility vehicle, and minivan models) they have usually been extra-cost options for this reason. Mass manufacturing and decades of improvement have reduced this cost gap.

Energy efficiency

Hydraulic automatic transmissions are almost always less energy efficient than manual transmissions due mainly to viscous and pumping losses; both in the torque converter and the hydraulic actuators. A relatively small amount of energy is required to pressurize the hydraulic control system, which uses fluid pressure to determine the correct shifting patterns and operate the various automatic clutch mechanisms.

Manual transmissions use a mechanical clutch to transmit torque, rather than a torque converter, thus avoiding the primary source of loss in an automatic transmission. Manual transmissions also avoid the power requirement of the hydraulic control system, by relying on the human muscle power of the vehicle operator to disengage the clutch and actuate the gear levers, and the mental power of the operator to make appropriate gear ratio selections. Thus the manual transmission requires very little engine power to function, with the main power consumption due to drag from the gear train being immersed in the lubricating oil of the gearbox.

The energy efficiency of automatic transmission has increased with the introduction of the torque converter lock-up clutch, which practically eliminates fluid losses when engaged. Modern automatic transmission also minimize energy usage and complexity, by minimizing the amount of shifting logic that is done hydraulically. Typically, control of the transmission has been transferred to computerized control systems which do not use fluid pressure for shift logic or actuation of clutching mechanisms.

The on road acceleration of an automatic transmission can occasionally exceed that of an otherwise identical vehicle equipped with a manual transmission in turbocharged diesel applications. Turbo-boost is normally lost between gear changes in a manual whereas in an automatic the accelerator pedal can remain fully depressed. This however is still largely dependent upon the number and optimal spacing of gear ratios for each unit, and whether or not the elimination of spooldown/accelerator lift off represent a significant enough gain to counter the slightly higher power consumption of the automatic transmission itself.

History and improvements

Modern automatic transmissions can trace their origins to an early "horseless carriage" gearbox that was developed in 1904 by the Sturtevant brothers of Boston, Massachusetts. This unit had two forward speeds, the ratio change being brought about by flyweights that were driven by the engine. At higher engine speeds, high gear was engaged. As the vehicle slowed down and engine RPM decreased, the gearbox would shift back to low.

Unfortunately, the metallurgy of the time wasn't up to the task, and owing to the abruptness of the gear change, the transmission would often fail without warning.

The next significant phase in the automatic transmission's development occurred in 1908 with the introduction of Henry Ford's remarkable Model T. The Model T, in addition to being cheap and reliable by the standards of the day, featured a simple, two speed plus reverse planetary transmission whose operation was manually controlled by the driver using pedals. The pedals actuated the transmission's friction elements (bands and clutches) to select the desired gear. In some respects, this type of transmission was less demanding of the driver's skills than the contemporary, unsynchronized manual transmission, but still required that the driver know when to make a shift, as well as how to get the car off to a smooth start.

In 1934, both REO and General Motors developed semi-automatic transmissions that were less difficult to operate than a fully manual unit. These designs, however, continued to use a clutch to engage the engine with the transmission. The General Motors unit, dubbed the "Automatic Safety Transmission," was notable in that it employed a power-shifting planetary gearbox that was hydraulically controlled and was sensitive to road speed, anticipating future development.

Parallel to the development in the 1930s of an automatically-shifting gearbox was Chrysler's work on adapting the fluid coupling to automotive use. Invented early in the 20th century, the fluid coupling was the answer to the question of how to avoid stalling the engine when the vehicle was stopped with the transmission in gear. Chrysler itself never used the fluid coupling with any of its automatic transmissions, but did use it in conjunction with a hybrid manual transmission called "Fluid Drive" (the similar Hy-Drive used a torque converter). These developments in automatic gearbox and fluid coupling technology eventually culminated in the introduction in 1939 of the General Motors Hydra-Matic, the world's first mass-produced automatic transmission.

Available as an option on 1940 Oldsmobiles and later Cadillacs, the Hydra-Matic combined a fluid coupling with three hydraulically-controlled planetary gearsets to produce four forward speeds plus reverse. The transmission was sensitive to engine throttle position and road speed, producing fully automatic up- and down-shifting that varied according to operating conditions.

The Hydra-Matic was subsequently adopted by Cadillac and Pontiac, and was sold to various other automakers, including Bentley, Hudson, Kaiser, Nash, and Rolls-Royce. It also found use during World War II in some military vehicles. From 1950-1954, Lincoln cars were also available with the Hydra-Matic. Mercedes-Benz subsequently devised a four-speed fluid coupling transmission that was similar in principle to the Hydra-Matic, but of a different design.

Interestingly, the original Hydra-Matic incorporated two features which are widely emulated in today's transmissions. The Hydra-Matic's ratio spread through the four gears produced excellent "step off" and acceleration in first, good spacing of intermediate

gears, and the effect of an overdrive in fourth, by virtue of the low numerical rear axle ratio used in the vehicles of the time. In addition, in third and fourth gear, the fluid coupling only handled a portion of the engine's torque, resulting in a high degree of efficiency. In this respect, the transmission's behavior was similar to modern units incorporating a lock-up torque converter.

In 1956, GM introduced the "Jetaway" Hydra-Matic, which was different in design than the older model. Addressing the issue of shift quality, which was an ongoing problem with the original Hydra-Matic, the new transmission utilized two fluid couplings, the primary one that linked the transmission to the engine, and a secondary one that replaced the clutch assembly that controlled the forward gearset in the original. The result was much smoother shifting, especially from first to second gear, but with a loss in efficiency and an increase in complexity. Another "innovation" for this new style Hydra-Matic was the appearance of a "Park" position on the selector. The original Hydra-Matic, which continued in production until the mid-1960s, still used the "Reverse" position for parking pawl engagement.

The first torque converter automatic, Buick's Dynaflow, was introduced for the 1948 model year. It was followed by Packard's Ultramatic in mid-1949 and Chevrolet's Powerglide for the 1950 model year. Each of these transmissions had only two forward speeds, relying on the converter for additional torque multiplication. In the early 1950s, BorgWarner developed a series of three-speed torque converter automatics for American Motors, Ford Motor Company, Studebaker, and several other manufacturers in the US and other countries. Chrysler was late in developing its own true automatic, introducing the two-speed torque converter PowerFlite in 1953, and the three-speed TorqueFlite in 1956. The latter was the first to utilize the Simpson compound planetary gearset.

General Motors produced multiple-turbine torque converters from 1954 to 1961. These included the Twin-Turbine Dynaflow and the triple-turbine Turboglide transmissions. The shifting took place in the torque converter, rather than through pressure valves and changes in planetary gear connections. Each turbine was connected to the drive shaft through a different gear train. These phased from one ratio to another according to demand, rather than shifting. The Turboglide actually had two speed ratios in reverse, with one of the turbines rotating backwards.

By the late 1960s, most of the fluid-coupling four-speed and two-speed transmissions had disappeared in favor of three-speed units with torque converters. Also around this time, whale oil was removed from automatic transmission fluid. By the early 1980s, these were being supplemented and eventually replaced by overdrive-equipped transmissions providing four or more forward speeds. Many transmissions also adopted the lock-up torque converter (a mechanical clutch locking the torque converter pump and turbine together to eliminate slip at cruising speed) to improve fuel economy.

As computerised engine control units (ECUs) became more capable, much of the logic built into the transmission's valve body was offloaded to the ECU. (Some manufacturers use a separate computer dedicated to the transmission, but sharing information with the

engine management computer.) In this case, solenoids turned on and off by the computer control shift patterns and gear ratios, rather than the spring-loaded valves in the valve body. This allows for more precise control of shift points, shift quality, lower shift times, and (on some newer cars) semi-automatic control, where the driver tells the computer when to shift. The result is an impressive combination of efficiency and smoothness. Some computers even identify the driver's style and adapt to best suit it.

ZF Friedrichshafen and BMW were responsible for introducing the first six-speed (the ZF 6HP26 in the 2002 BMW E65 7-Series). Mercedes-Benz's 7G-Tronic was the first seven-speed in 2003, with Toyota introducing an eight-speed in 2007 on the Lexus LS 460. Derived from the 7G-Tronic, Mercedes-Benz unveiled a semi-automatic transmission with the torque converter replaced with a wet multi clutch called the AMG SPEEDSHIFT MCT.

Automatic transmission models

Some of the best known automatic transmission families include:

- General Motors — Powerglide, "Turbo-Hydramatic" TH350, TH400 and 700R4, 4L60-E, 4L80-E, Holden Trimatic
- Ford: Cruise-O-Matic, C4, C6, AOD/AODE, E4OD, ATX, AXOD/AX4S/AX4N
- Chrysler: TorqueFlite 727 and 904, A500, A518, 45RFE, 545RFE
- BorgWarner (later Aisin AW)
- ZF Friedrichshafen automatic transmissions
- Allison Transmission
- Voith Turbo
- Aisin AW; Aisin AW is a Japanese automotive parts supplier, known for its automatic transmissions and navigation systems
- Honda
- Nissan/Jatco
- Volkswagen Group - 01M
- Drivetrain Systems International (DSI) - M93, M97 and M74 4-speeds, M78 and M79 6-speeds

Automatic transmission families are usually based on Ravigneaux, Lepelletier , or Simpson planetary gearsets. Each uses some arrangement of one or two central sun gears, and a ring gear, with differing arrangements of planet gears that surround the sun and mesh with the ring. An exception to this is the Hondamatic line from Honda, which uses sliding gears on parallel axes like a manual transmission without any planetary gearsets. Although the Honda is quite different from all other automatics, it is also quite different from an automated manual transmission (AMT).

Many of the above AMTs exist in modified states, which were created by racing enthusiasts and their mechanics by systematically re-engineering the transmission to achieve higher levels of performance. These are known as "performance transmissions".

An example of a manufacturer of high performance transmissions of General Motors and Ford transmissions is PerformaBuilt.

Continuously variable transmissions

A fundamentally different type of automatic transmission is the *continuously variable transmission* or *CVT*, which can smoothly and steplessly alter its gear ratio by varying the diameter of a pair of belt or chain-linked pulleys, wheels or cones. Some continuously variable transmissions use a hydrostatic drive — consisting of a variable displacement pump and a hydraulic motor — to transmit power without gears. CVT designs are usually as fuel efficient as manual transmissions in city driving, but early designs lose efficiency as engine speed increases.

A slightly different approach to CVT is the concept of *toroidal CVT* or *infinitely variable transmission* (IVT). These concepts provide zero and reverse gear ratios.

Some current hybrid vehicles, notably those of Toyota, Lexus and Ford Motor Company, have an "electronically-controlled CVT" (E-CVT). In this system, the transmission has fixed gears, but the ratio of wheel-speed to engine-speed can be continuously varied by controlling the speed of the third input to a differential using an electric motor-generator.

Manually controlled automatic transmissions

Most automatic transmissions offer the driver a certain amount of manual control over the transmission's shifts (beyond the obvious selection of forward, reverse, or neutral). Those controls take several forms:

Throttle kickdown
: Most automatic transmissions include some means of forcing a downshift into the lowest possible gear ratio if the throttle pedal is fully depressed. In many older designs, kickdown is accomplished by mechanically actuating a valve inside the transmission. Most modern designs use a solenoid-operated valve that is triggered by a switch on the throttle linkage or by the engine control unit (ECM) in response to an abrupt increase in engine power.

Mode selection
: Allows the driver to choose between preset shifting programs. For example, 'Economy mode' saves fuel by upshifting at lower engine speeds, while 'Sport mode' (aka Power or Performance) delays shifting for maximum acceleration. The modes also change how the computer responds to throttle input.

Low gear ranges
: Conventionally, automatic transmissions have selector positions that allow the driver to limit the maximum ratio that the transmission may engage. On older transmissions, this was accomplished by a mechanical lockout in the transmission valve body preventing an upshift until the lockout was disengaged; on computer-controlled transmissions, the same effect is accomplished by firmware. The

transmission can still upshift and downshift automatically between the remaining ratios: for example, in the *3* range, a transmission could shift from first to second to third, but not into fourth or higher ratios. Some transmissions will still upshift automatically into the higher ratio if the engine reaches its maximum permissible speed in the selected range.

Manual controls

Some transmissions have a mode in which the driver has full control of ratio changes (either by moving the selector, or through the use of buttons or paddles), completely overriding the automated function of the hydraulic controller. Such control is particularly useful in cornering, to avoid unwanted upshifts or downshifts that could compromise the vehicle's balance or traction. "Manumatic" shifters, first popularized by Porsche in the 1990s under the trade name Tiptronic, have become a popular option on sports cars and other performance vehicles. With the near-universal prevalence of electronically controlled transmissions, they are comparatively simple and inexpensive, requiring only software changes, and the provision of the actual manual controls for the driver. The amount of true manual control provided is highly variable: some systems will override the driver's selections under certain conditions, generally in the interest of preventing engine damage. Since these gearboxes also have a throttle kickdown switch, it is impossible to fully exploit the engine power at low to medium engine speeds.

Second gear takeoff

Some automatics, particularly those fitted to larger capacity or high torque engines, either when '2' is manually selected, or by engaging a "winter mode", will start off in second gear instead of first, and then not shift into a higher gear until returned to D. Also note that as with most American automatic transmissions, selecting "2" using the selection lever will not tell the transmission to be in only 2nd gear, rather, it will simply limit the transmission to 2nd gear after prolonging the duration of 1st gear through higher speeds than normal operation. The 2000-2002 Lincoln LS V8 (the five-speed automatic *without* manumatic capabilities (as opposed to the optional sport package w/ manu-matic 5sp) started in 2nd gear during most starts both in winter and summer by selecting the "D5" transmission selection notch in the shiftgate (For fuel savings), whereas "D4" would always start in 1st gear. This is done to reduce torque multiplication when proceeding forward from a standstill in conditions where traction was limited — on snow- or ice-covered roads, for example.

Some automatic transmissions modified or designed specifically for drag racing may also incorporate a transmission brake, or "trans-brake," as part of a manual valve body. Activated by electrical solenoid control, a trans-brake simultaneously engages the first and reverse gears, locking the transmission and preventing the input shaft from turning. This allows the driver of the car to raise the engine RPM against the resistance of the torque converter, then launch the car by simply releasing the trans-brake switch.

Chapter 5

Semi-Automatic Transmission

A semi-automatic transmission is one that cannot change gears automatically but only half-automatically. ("Semi" meaning half in Latin.) This requires the driver to intervene in order to execute a gear change by moving a gear lever or pressing a clutch pedal or actuating a switch lever or other action. An **automated transmission** (also known as **self-changing transmission**, **clutchless manual transmission**, automated manual transmission, flappy-paddle gearbox, or paddle shift gearbox) is a system which uses electronic sensors, pneumatics, processors and actuators to execute gear shifts on the command of the driver or by a computer. This removes the need for a clutch pedal which the driver otherwise needs to depress before making a gear change, since the clutch itself is actuated by electronic equipment which can synchronise the timing and torque required to make gear shifts quick and smooth. The system was designed by automobile manufacturers to provide a better driving experience, especially in cities where congestion frequently causes stop-and-go traffic patterns.

Many modern automated transmissions can also operate in the same manner as a conventional type of automatic transmission by allowing the transmission's computer to automatically change gear if, for example, the driver were redlining the engine. The ability to shift gears manually, often via paddle shifters, can also be found on certain automatic transmissions (manumatics such as Tiptronic) and continuous variable transmissions (CVTs) (such as Lineartronic). Despite superficial similarity to other automated transmissions, automated transmissions differ significantly in internal operation and driver's "feel" from manumatics and CVTs. A manumatic, like a standard automatic transmission, uses a torque converter instead of clutch to manage the link between the transmission and the engine, while a CVT uses a belt instead of a fixed number of gears.

The automated transmission may be derived from a conventional automatic; for instance Mercedes-Benz's AMG SPEEDSHIFT MCT automated transmission is based on the 7G-Tronic manumatic, however the latter's torque converter has been replaced with a wet, multi-plate launch clutch.. Other automateds have their roots in a conventional manual; the SMG II drivelogic (found in the BMW M3 (E46) is a Getrag 6-speed manual

transmission, but with an electrohydraulically actuated clutch pedal, similar to an Formula One style transmission.

Operation

Steering wheel of Ferrari F430 with paddle-shifters

In standard mass-production automobiles, the gear lever appears similar to manual shifts, except that the gear stick only moves forward and backward to shift into higher and lower gears, instead of the traditional H-pattern. The Bugatti Veyron uses this approach for its seven-speed transmission. In Formula One, the system is adapted to fit onto the steering wheel in the form of two paddles; depressing the right paddle shifts into a higher gear, while depressing the left paddle shifts into a lower one. Numerous road cars have inherited the same mechanism.

Hall effect sensors sense the direction of requested shift, and this input, together with a sensor in the gear box which senses the current speed and gear selected, feeds into a central processing unit. This unit then determines the optimal timing and torque required for a smooth clutch engagement, based on input from these two sensors as well as other factors, such as engine rotation, the Electronic Stability Control, air conditioner and dashboard instruments.

The central processing unit powers a hydro-mechanical unit to either engage or disengage the clutch, which is kept in close synchronization with the gear-shifting action the driver has started. In some cases, the hydro-mechanical unit contains a servomotor coupled to a gear arrangement for a linear actuator, which uses brake fluid from the braking system to impel a hydraulic cylinder to move the main clutch actuator. In other cases, the clutch actuator may be completelly electric.

The power of the system lies in the fact that electronic equipment can react much faster and more precisely than a human, and takes advantage of the precision of electronic signals to allow a complete clutch operation without the intervention of the driver.

For the needs of parking, reversing and neutralizing the transmission, the driver must engage both paddles at once, after this has been accomplished the car will prompt for one of the three options.

The clutch is really only needed to start the car. For a quicker upshift, the engine power can be cut, and the collar disengaged until the engine drops to the correct speed for the next gear. For the teeth of the collar to slide into the teeth of the rings, both the speed and position must match. This needs sensors to measure not only the speed, but the positions of the teeth, and the throttle may need to be opened softer or harder. The even-faster shifting techniques like powershifting require a heavier gearbox or clutch or even a dual clutch transmission.

History

Racing

According to the Car Crazy episode "Le Mans Museum of the Automobile", the paddle shifter interface could be found as early as 1912. The system used an inner steering wheel to select a gear level and can be seen on the "Bollée Type F Torpédo" of 1912, on show at the "Musée Automobile de la Sarthe" at the Le Mans race circuit.

In Formula One, the first attempt at clutch-less gear changing was in the early 1970s, with the system being tested by the Lotus team. However, it would be much later that attention was turned back to the concept. In 1989, John Barnard and Harvey Postlethwaite, then-Ferrari engineers and designers, created a automated gearbox for use in the Ferrari 640 single-seater. Despite serious problems in testing, the car won its first race at the hands of Nigel Mansell. By 1994, the automated transmission was dominant in terms of gearbox technology, and the last F1 car fitted with a manual gearbox raced in 1995.

After concerns that the technology allowed software engineers to pre-program the cars to automatically change to the optimum gear according to the position on the track, without any driver intervention, a standardized software system was mandated, ensuring the gears would only change up or down when instructed to by the driver. Buttons on the steering wheel, which go directly to a certain gear—rather than sequentially—are still permitted.

Chrysler

Historically, the first automated transmission which was marketed by a major manufacturer was the 1941 M4/Vacamatic Transmission by Chrysler. It was an attempt to compete against rivals' automatic transmissions, though it still had a clutch, it was primarily used to change range. The main difference was the addition of a fluid coupling between engine and clutch, and the shifting mechanism.

In normal driving, the clutch was not used. The transmission itself was a fully synchronised manual type, with four forward gears, one reverse, where the shifting was done 'automatically' by either vacuum cylinders (early, M4, Vacamatic), or hydraulic cylinders (late, M6, Presto-Matic).

Packard

Nearly simultaneously, Packard introduced the Electro-Matic clutch, which was a vacuum operated clutch pedal, signaled by the position of the accelerator. Significantly, it came with an 'off' switch, probably due to the fact that the system was somewhat unstable during engine warm-up. Packard's system was used in conjunction with their regular transmission so the H-pattern shifting remained.

Earlier, and by many manufacturers, an arrangement to disengage the clutch during coasting was tried to ease shifting. Called "freewheeling", it was bedeviled by the absence of adequate brakes.

Volkswagen

In later production years, the Volkswagen Beetle offered an optional "Autostick", which was essentially a clutchless manual with three forward gears, using the Saxomat auto-clutch.

Renault

For the Renault 8, a automated transmission was offered in 1965. It was produced by Jaeger, and consisted of a three speed electrically operated gearbox and a powder ferromagnetic coupler.

Mercedes-Benz

Mercedes used a system similar to the VW Autostick, called Hydrak. Hydrak had one major flaw- the oil supply for the torque converter was sealed within the converter itself and did not circulate via a pump, and also had no oil cooler. Idling in gear for even short periods would overheat the oil and burn up the seals in the converter, which would then need to be replaced.

Citroën

Citroën produced a number of variants on automated transmission. The Citroën DS, introduced in 1955, used a hydraulic system to select gears and operate the conventional clutch using hydraulic servos. There was also a speed controller and idle speed step-up device, all hydraulically operated. This allowed clutchless shifting with a single selector mounted behind the steering wheel. This system was nicknamed 'Citro-Matic' in the U.S.

The Citroën 2CV gained an optional centrifugal clutch, marketed in English-speaking countries as "Trafficlutch". It did not help with gear changing, but it disengaged automatically when the engine slowed to an idle. A device was fitted to the carburettor to prevent the throttle closing abruptly, and the resultant clutch disengagement and lack of engine braking.

Later, the manufacturer introduced optional automated transmissions on their medium and large saloon and estate models in the 1970s; the Citroën GS and CX models had the option of three-speed, automated transmission marketed as 'C matic'. This was simpler than the DS implementation: instead of hydraulics it used a floor mounted quadrant lever operating conventional gear selector rods and an electrically controlled wet plate clutch in conjunction with a torque converter. The torque converter gave more of the feel of a conventional automatic transmission, which was completely lacking in the DS. Citroën automated transmission of this era made no use of electronics: the entire gear selecting operation was carried out by simply moving the gear lever from one ratio to the next.

NSU

The German automobile manufacturer NSU produced a automated system for the rotary-engined Ro80 saloon car in the 1960s, similar in concept to Citroën's system except that it used an electric switch on the gear shifter which disengaged the clutch.

Honda

Honda marketed both cars and motorcycles with the Hondamatic transmission in the 1970s and early 1980s. This transmission is frequently referred to as the 'Bang-O-Matic' by mechanics. The design is noteworthy because it preserves engine braking by eliminating a sprag between first and second gears.

Daihatsu

The 993 cc Daihatsu Charade in 1985 at least had the option of a two-speed automated transmission, which was similar to a conventional auto with torque converter and planetary gearset but lacked a full valve body for making decisions regarding shifting. This was left entirely to the driver and as a result could be accelerated from rest in top gear if desired, depending entirely on the torque converter action. The standing ¼mile time with two 60 kg (130 lb) occupants and using low gear appropriately was 21.0 sec while using top gear only was 21.5 sec.

Ferrari

Ferrari's first automated gearbox in a road car (They had used them previously in their Formula One cars since 1989) went on sale in 1997 in the Ferrari F355. The most recent iteration of its robotised manual came forward in the Ferrari 599 GTO which was capable of changing gear in 60 ms. In the new Ferrari California & Ferrari 458 Italia, Ferrari has opted to use a double-clutch transmission.

Vauxhall

Vauxhall Motors in Great Britain (Opel in continental Europe) produced a automated transmission gearbox, the Easytronic gearbox. As with all standard automateds, the Easytronic car has only two pedals (accelerator pedal and brake pedal) but it does have a clutch, though this is inbuilt into the car and is electrohydraulic. The Easytronic can be driven in "manual mode" simply by using the paddle shifter selector to change gears if the driver wishes to do so, or alternatively it can be driven in exactly the same way as a fully conventional automatic—however, many Easytronic owners have complained that gear shifts in "automatic mode" are jerky; a common complaint with semi-autos based on a conventional manual gearbox. As with conventional, full automatic transmission cars, the Easytronic will "creep" forwards when the driver's foot is released from the brake pedal when the car is stationary.

Other applications

Trucks, buses, and trains

Automated transmissions have also made its way into the truck and bus market in the early 2000s. Volvo offers its I-shift on its heavier trucks and buses, while ZF markets its ASTronic system for trucks, buses and coaches. In North America, Eaton offers the "AutoShift" system which is an add-on to traditional non-synchromesh manual transmissions for heavy trucks. These gearboxes have a place in public transport as they have been shown to reduce fuel consumption in some specific cases.

Bristol/Leyland Buses

The British employed Pneumatic valve bodies to regulate gear shifting by charging pistons with compressed air within the gearbox. These pneumatic pistons or gear-levers are activated by a series of valve bodies and controlled by electronic actuators linked to the gear shifter. As each gear cycle is energized, air valves open and close to engage the corresponding gear-lever. Compressed air is drawn from the braking system and in the event of loss of pressure, the transmission will remain in the last gear selected or if in neutral, will not shift into gear.

In the UK though, automated transmission has been very popular on buses for some time, from the 1950s right through to the 1980s, an example being the well known London Routemaster, although the latter could also be driven as a fully automatic in the three

highest gears. Most heavy-duty bus manufacturers offered this option, using a gearbox from Self-Changing Gears Ltd of Coventry, and on urban single- and double-deck buses it was the norm by the 1970s. This coincided with the development of city buses with engines and transmissions at the rear rather than the front, which was beyond the capability of a manual gearchange/clutch linkage from the driver's position. Leyland manufactured many buses with automated transmission, including its Leopard and Tiger coaches. Fully automatic transmission became popular with increasing numbers of continental buses being bought in the UK, and more and more British manufacturers began offering automatic options, mostly using imported gearboxes, and automated transmission lost favour. These days, very few buses with automated transmission remain in service, although many are still on the roads with private owners. Modern types of automated transmission though is becoming more common, mostly replacing manual gearboxes in coaches and small buses.

The Self-Changing Gears automated gearbox was also fitted to the several thousand diesel railcars built for the British railway system in the late 1950s-early 1960s, which lasted in service until the 1990s-2000s. Their whole engine-transmission system was based on that from the main bus manufacturers of the period such as Leyland and AEC. Gear selection was by the train driver with a hand-held lever as the train accelerated. Such trains were formed of a number of such railcars coupled together and each power car had two engine/automated gearbox units mounted under the floor. Synchronising controls by control cables connected through the train ensured all the gearboxes under all coaches of the train changed gear together.

Motorcycles

In addition to the Hondamatic system noted above, Yamaha Motor Company introduced a automated transmission on its 2007 model year FJR1300 sport-touring motorcycle in 2006. Notably, this system can be shifted either with the lever in the traditional position near the left foot, or with a switch accessible to the left hand where the clutch lever would go on traditional motorcycles.

Honda has begun production of the VFR1200F, which includes an optional dual clutch transmission, the first to be fitted to a motorcycle.

ATVs

Honda released automated electric shift ATVs starting in model year 1998 with the TRX450FE aka Foreman 450ES ESP (Electric Shift Program). Shifting is accomplished by pressing either one of the gear selector arrows on the left handlebar control. The current selected gear is indicated by a digital display. The primary components of the shifting mechanisms were the same on both the manual and electric shift models, but the major difference was the deletion of the shift pedal and the addition of an internal electric shift servo which actuated the components (clutch assy, shift drum, etc.)in one motion instead of the traditional foot lever. In the event of a malfunction, a supplied override lever can be placed on a shaft protruding from the crankcase in the traditional spot where

the pedal would have been. This electric shift technology was later applied to their complete line of ATVs.

Marketing names

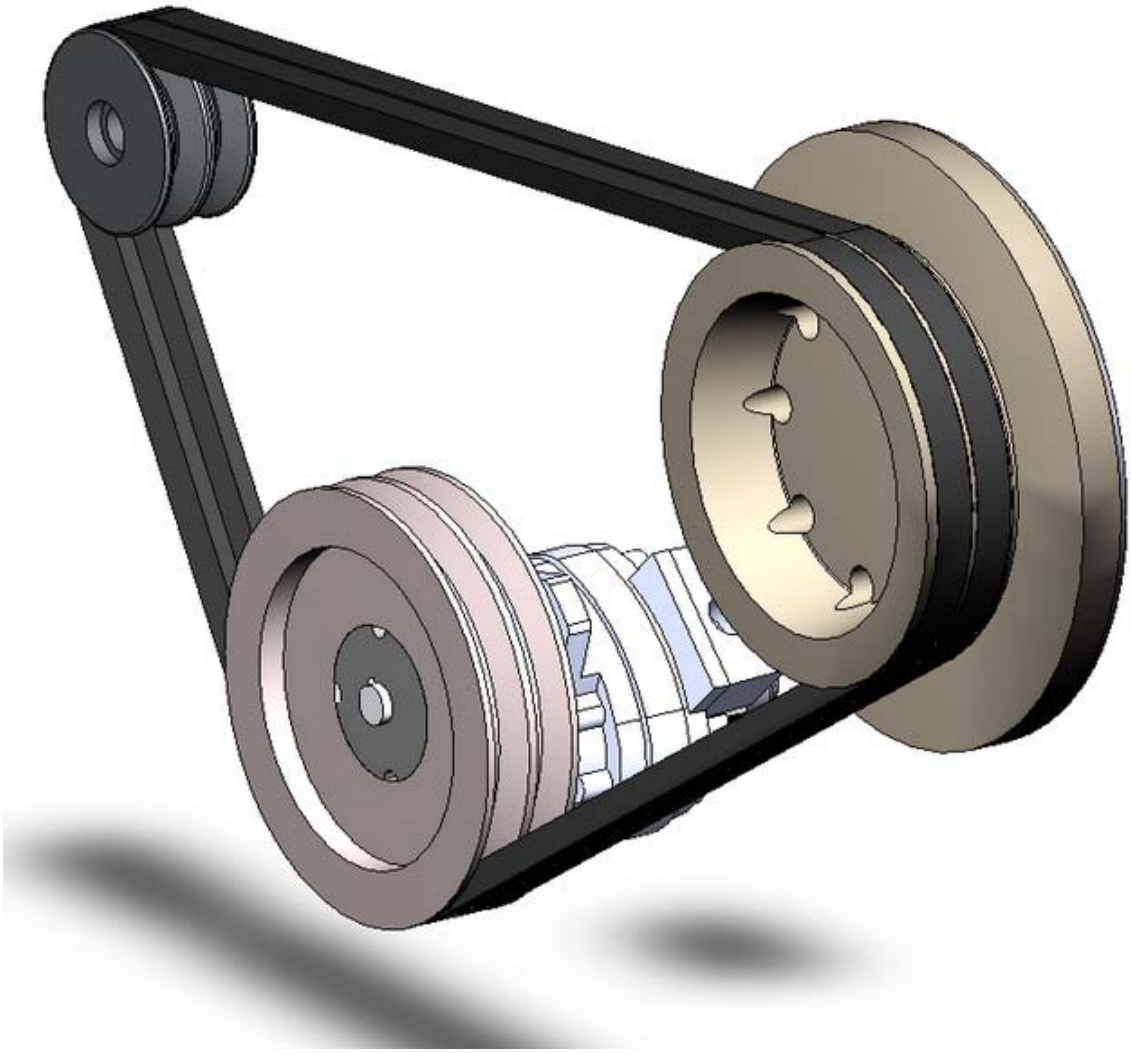
- 2-tronic, EGC (Electric Gearbox Control) or Piloted Manual – Peugeot
- Twin Clutch SST – Mitsubishi
- Dual clutch transmission (DCT), a generic term – Volkswagen Group, Bugatti, Koenigsegg
- Direct-Shift Gearbox (DSG) – Volkswagen Group: SEAT, Skoda Auto, Volkswagen
    - S tronic – Audi
- Dualogic – Fiat
- Duo Select – Maserati
- Durashift EST – Ford
- E-Gear – Lamborghini
- Easytronic – Opel / Vauxhall
- Multimode manual transmission – Toyota
- PDK (Porsche Doppelkupplungen)/Sportomatic (Clutchless manual pre-1969) – Porsche
- Pleasure Shift – Saleen
- Quickshift – Renault
- Retrotek, MasterShift, Twist Machine, etc. – Detroit's Big 3
- Sensonic or ACS – Saab
- Selespeed – Alfa Romeo, Fiat
- SensoDrive or EGS (Electronic Gearbox System) or BMP – Citroen
- Steptronic, SMG/SSG (Electrohydraulic manual transmission) – BMW
- Speedgear – Fiat
- Sportshift – Aston Martin
- MasterShift – Aftermarket

Types

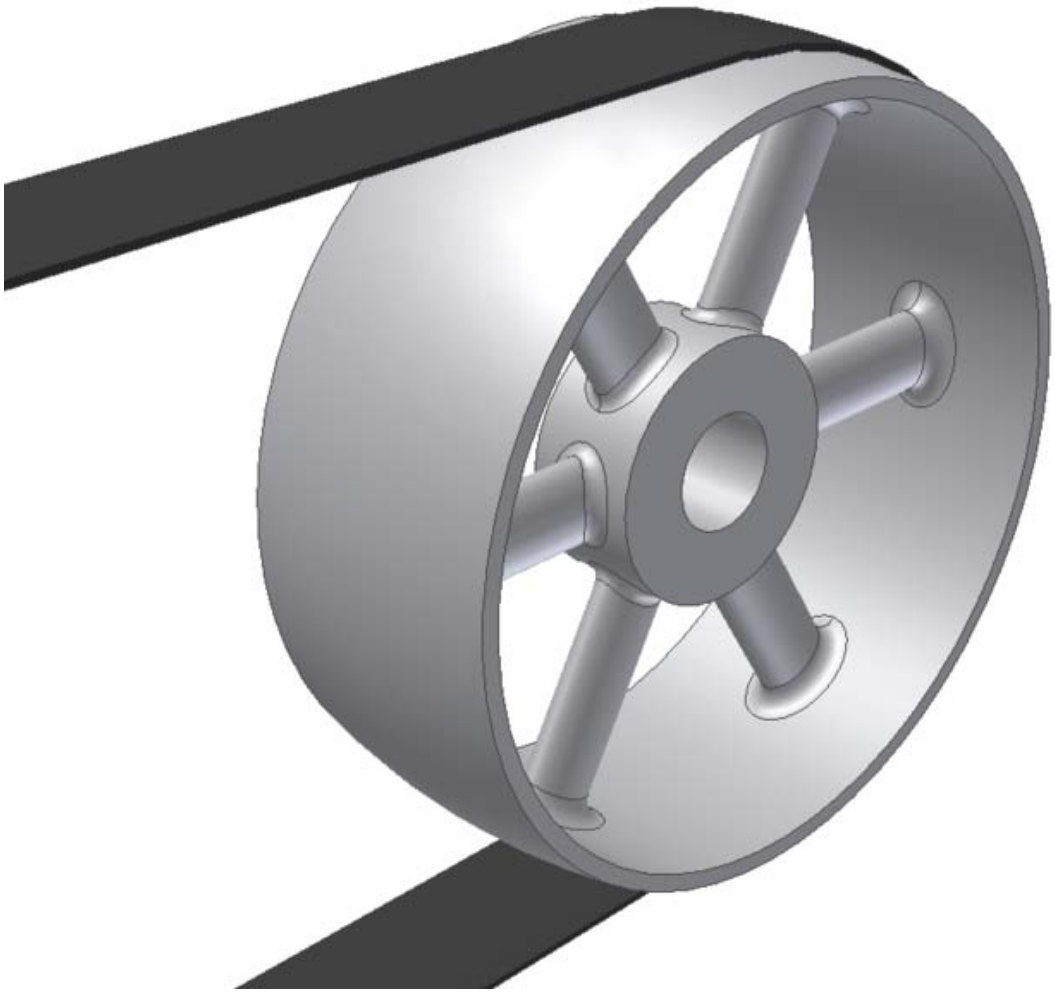
- Dual clutch transmission
- Electrohydraulic manual transmission (e.g., BMW sequential manual gearbox, SMG)
- Saxomat
- Multimode manual transmission

Chapter 6

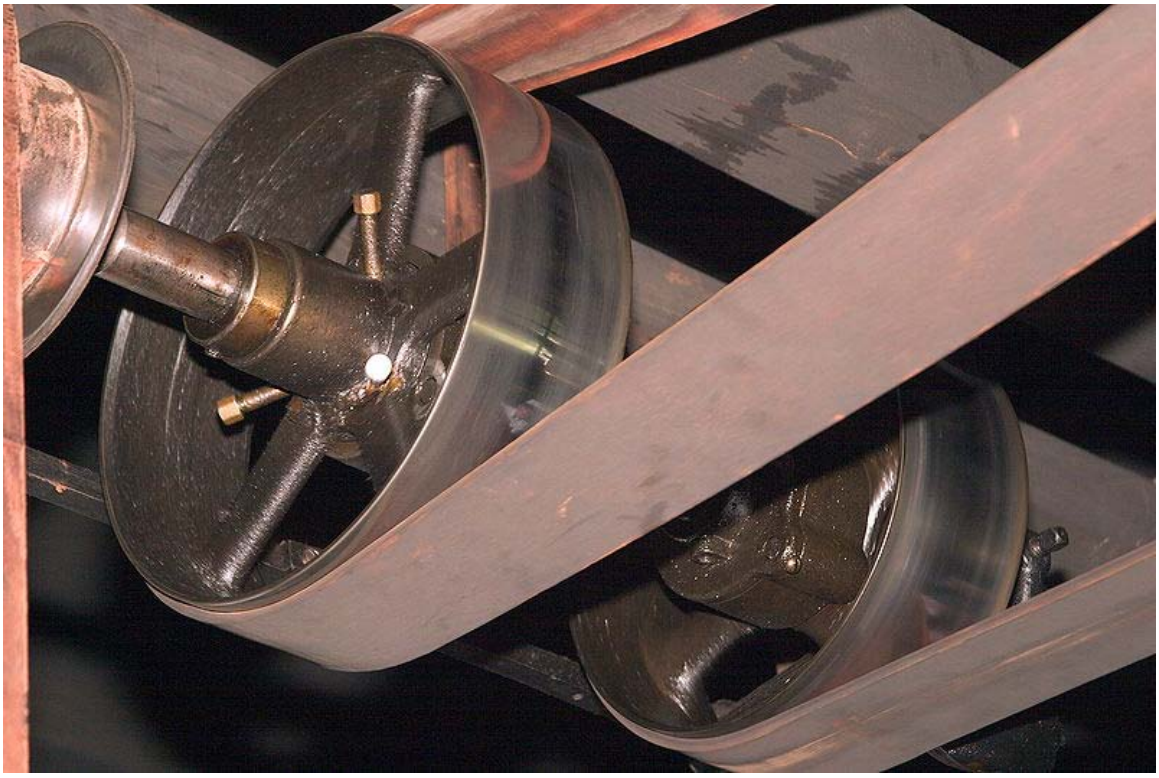
Belt (Mechanical)



A pair of vee-belts



flat belt



Flat belt drive in the machine shop at the Hagley Museum

A **belt** is a loop of flexible material used to link two or more rotating shafts mechanically. Belts may be used as a source of motion, to transmit power efficiently, or to track relative movement. Belts are looped over pulleys. In a two pulley system, the belt can either drive the pulleys in the same direction, or the belt may be crossed, so that the direction of the shafts is opposite. As a source of motion, a conveyor belt is one application where the belt is adapted to continually carry a load between two points.

Power transmission

Belts are the cheapest utility for power transmission between shafts that may not be axially aligned. Power transmission is achieved by specially designed belts and pulleys. The demands on a belt drive transmission system are large and this has led to many variations on the theme. They run smoothly and with little noise, and cushion motor and bearings against load changes, albeit with less strength than gears or chains. However, improvements in belt engineering allow use of belts in systems that only formerly allowed chains or gears.

Pros and cons

Belt drive, moreover, is simple, inexpensive, and does not require axially aligned shafts. It helps protect the machinery from overload and jam, and damps and isolates noise and vibration. Load fluctuations are shock-absorbed (cushioned). They need no lubrication

and minimal maintenance. They have high efficiency (90-98%, usually 95%), high tolerance for misalignment, and are inexpensive if the shafts are far apart. Clutch action is activated by releasing belt tension. Different speeds can be obtained by step or tapered pulleys.

The angular-velocity ratio may not be constant or equal to that of the pulley diameters, due to slip and stretch. However, this problem has been largely solved by the use of toothed belts. Temperatures ranges from −31 °F (−35 °C) to 185 °F (85 °C). Adjustment of center distance or addition of an idler pulley is crucial to compensate for wear and stretch.

Flat belts

The drive belt: used to transfer power from the engine's flywheel. Here shown driving a threshing machine.

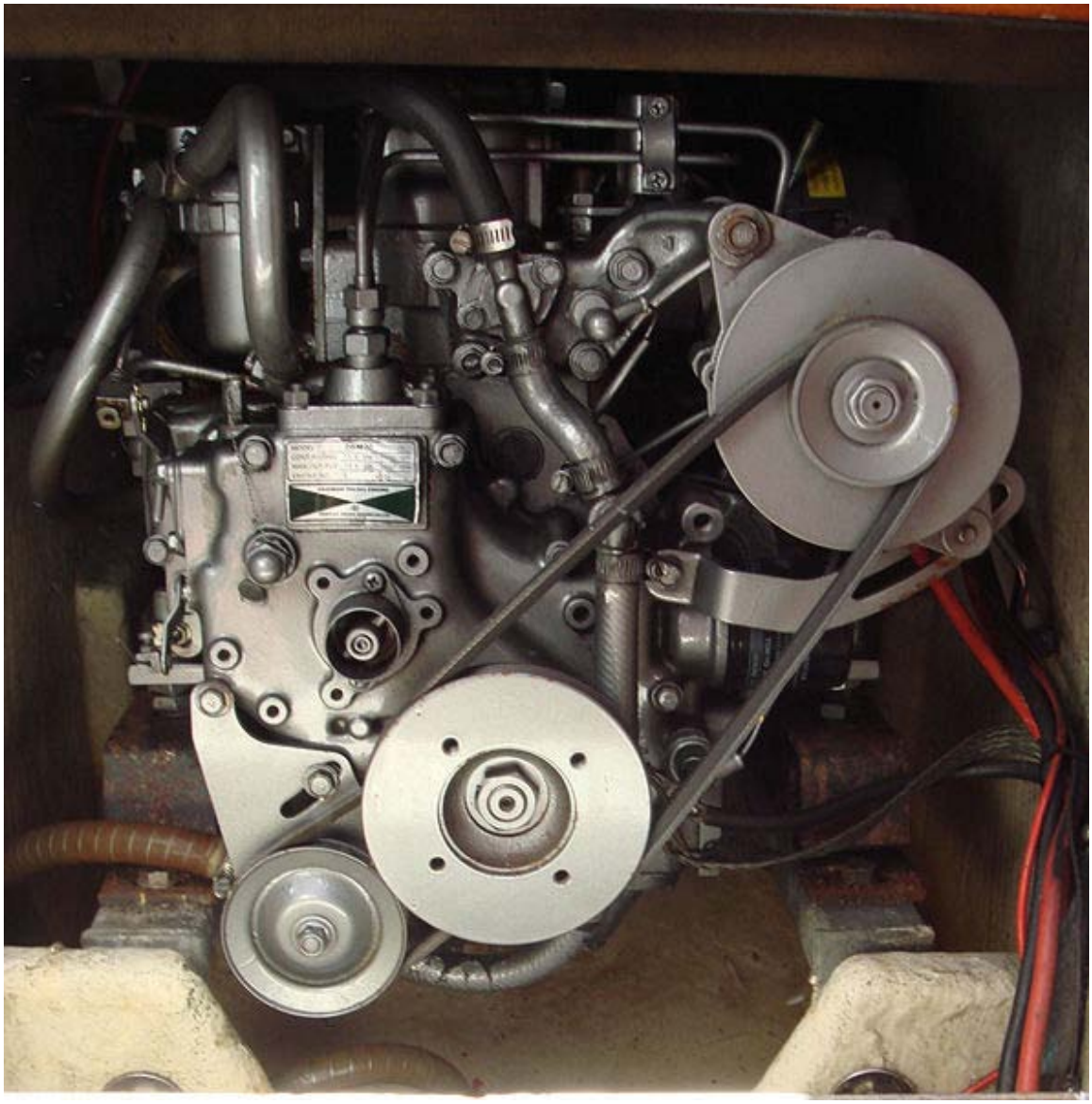
Flat belts were used early in line shafting to transmit power in factories. They were also used in countless farming, mining, and logging applications, such as bucksaws, sawmills, threshers, silo blowers, conveyors for filling corn cribs or haylofts, balers, water pumps (for wells, mines, or swampy farm fields), and electrical generators. The flat belt is a simple system of power transmission that was well suited for its day. It delivered high power for high speeds (500 hp for 10,000 ft/min), in cases of wide belts and large pulleys. These drives are bulky, requiring high tension leading to high loads, so vee belts have mainly replaced the flat-belts except when high speed is needed over power. The Industrial Revolution soon demanded more from the system, and flat belt pulleys needed to be carefully aligned to prevent the belt from slipping off. Because flat belts tend to climb towards the higher side of the pulley, pulleys were made with a slightly convex or

"crowned" surface (rather than flat) to keep the belts centered. Flat belts also tend to slip on the pulley face when heavy loads are applied and many proprietary dressings were available that could be applied to the belts to increase friction, and so power transmission. Grip was better if the belt was assembled with the hair (i.e. outer) side of the leather against the pulley although belts were also often given a half-twist before joining the ends (forming a Möbius strip), so that wear was evenly distributed on both sides of the belt (DB). Belts were joined by lacing the ends together with leather thonging, or later by steel comb fasteners. A good modern use for a flat belt is with smaller pulleys and large central distances. They can connect inside and outside pulleys, and can come in both endless and jointed construction.

Round belts

Round belts are a circular cross section belt designed to run in a pulley with a circular (or near circular) groove. They are for use in low torque situations and may be purchased in various lengths or cut to length and joined, either by a staple, gluing or welding (in the case of polyurethane). Early sewing machines utilized a leather belt, joined either by a metal staple or glued, to a great effect.

Vee belts



Belts on a Yanmar 2GM20 marine diesel engine.

A multiple-V-belt drive on an air compressor.

Vee belts (also known as V-belt or wedge rope) solved the slippage and alignment problem. It is now the basic belt for power transmission. They provide the best combination of traction, speed of movement, load of the bearings, and long service life. The V-belt was developed in 1917 by John Gates of the Gates Rubber Company. They are generally endless, and their general cross-section shape is trapezoidal. The "V" shape of the belt tracks in a mating groove in the pulley (or sheave), with the result that the belt cannot slip off. The belt also tends to wedge into the groove as the load increases — the greater the load, the greater the wedging action — improving torque transmission and making the V-belt an effective solution, needing less width and tension than flat belts. V-belts trump flat belts with their small center distances and high reduction ratios. The preferred center distance is larger than the largest pulley diameter, but less than three times the sum of both pulleys. Optimal speed range is 1000–7000 ft/min. V-belts need larger pulleys for their larger thickness than flat belts. They can be supplied at various fixed lengths or as a segmented section, where the segments are linked (spliced) to form a belt of the required length. For high-power requirements, two or more vee belts can be joined side-by-side in an arrangement called a multi-V, running on matching multi-groove sheaves. The strength of these belts is obtained by reinforcements with fibers like steel, polyester or aramid (e.g. Twaron or Kevlar). This is known as a multiple-V-belt drive (or sometimes a "classical V-belt drive"). When an endless belt does not fit the need, jointed and link V-belts may be employed. However they are weaker and only

usable at speeds up to 4000 ft/min. A link v-belt is a number of rubberized fabric links held together by metal fasteners. They are length adjustable by disassembling and removing links when needed.

Multi-groove belts

A multi-groove or polygroove belt is made up of usually 5 or 6 "V" shapes along side each other. This gives a thinner belt for the same drive surface, thus is more flexible, although often wider. The added flexibility offers an improved efficiency, as less energy is wasted in the internal friction of continually bending the belt. In practice this gain of efficiency is overshadowed by the reduced heating effect on the belt, as a cooler-running belt lasts longer in service.

A further advantage of the polygroove belt, and the reason they have become so popular, stems from the ability to be run over pulleys on the ungrooved back of the belt. Although this is sometimes done with vee belts and a single idler pulley for tensioning, a polygroove belt may be wrapped around a pulley on its back tightly enough to change its direction, or even to provide a light driving force.

Any vee belt's ability to drive pulleys depends on wrapping the belt around a sufficient angle of the pulley to provide grip. Where a single-vee belt is limited to a simple convex shape, it can adequately wrap at most three or possibly four pulleys, so can drive at most three accessories. Where more must be driven, such as for modern cars with power steering and air conditioning, multiple belts are required. As the polygroove belt can be bent into concave paths by external idlers, it can wrap any number of driven pulleys, limited only by the power capacity of the belt.

This ability to bend the belt at the designer's whim allows it to take a complex or "serpentine" path. This can assist the design of a compact engine layout, where the accessories are mounted more closely to the engine block and without the need to provide movable tensioning adjustments. The entire belt may be tensioned by a single idler pulley.

Ribbed belt

A ribbed belt is a power transmission belt featuring lengthwise grooves. It operates from contact between the ribs of the belt and the grooves in the pulley. Its single-piece structure it reported to offer an even distribution of tension across the width of the pulley where the belt is in contact, a power range up to 600 kW, a high speed ratio, serpentine drives (possibility to drive off the back of the belt), long life, stability and homogeneity of the drive tension, and reduced vibration. The ribbed belt may be fitted on various applications : compressors, fitness bikes, agricultural machinery, food mixers, washing machines, lawn mowers, etc.

Film belts

Though often grouped with flat belts, they are actually a different kind. They consist of a very thin belt (0.5-15 millimeters or 100-4000 micrometres) strip of plastic and occasionally rubber. They are generally intended for low-power (10 hp or 7 kW), high-speed uses, allowing high efficiency (up to 98%) and long life. These are seen in business machines, printers, tape recorders, and other light-duty operations.

Timing belts

Timing belt

Belt-drive cog on a belt-driven bicycle

Timing belts, (also known as **Toothed**, **Notch**, **Cog**, or **Synchronous** belts) are a *positive* transfer belt and can track relative movement. These belts have teeth that fit into a matching toothed pulley. When correctly tensioned, they have no slippage, run at constant speed, and are often used to transfer direct motion for indexing or timing purposes (hence their name). They are often used in lieu of chains or gears, so there is less noise and a lubrication bath is not necessary. Camshafts of automobiles, miniature timing systems, and stepper motors often utilize these belts. Timing belts need the least tension of all belts, and are among the most efficient. They can bear up to 200 hp (150 kW) at speeds of 16,000 ft/min.

Timing belts with a helical offset tooth design are available. The helical offset tooth design forms a chevron pattern and causes the teeth to engage progressively. The chevron pattern design is self-aligning. The chevron pattern design does not make the noise that some timing belts make at idiosyncratic speeds, and is more efficient at transferring power (up to 98%).

Disadvantages include a relatively high purchase cost, the need for specially fabricated toothed pulleys, less protection from overloading and jamming, and the lack of clutch action.

Specialty belts

Belts normally transmit power on the tension side of the loop. However, designs for continuously variable transmissions exist that use belts that are a series of solid metal blocks, linked together as in a chain, transmitting power on the compression side of the loop.

Rolling roads

Belts used for rolling roads for wind tunnels can be capable of 250 km/h.

Flying rope

For transmission of mechanical power over distance without electrical energy, a flying rope can be used. A wire or manila rope can be used to transmit mechanical energy from a steam engine or water wheel to a factory or pump which is located a considerable distance (10 to 100s of meters or more) from the power source. A flying rope way could be supported on poles and pulleys similar to the cable on a chair lift or aerial tramway. Transmission efficiency is generally high.

Standards for use

The open belt drive has parallel shafts rotating in the same direction, whereas the cross-belt drive also bears parallel shafts but rotate in opposite direction. The former is far more common, and the latter not appropriate for timing and standard V-belts, because the pulleys contact both the both inner and outer belt surfaces. Nonparallel shafts can be connected if the belt's center line is aligned with the center plane of the pulley. Industrial belts are usually reinforced rubber but sometimes leather types, non-leather non-reinforced belts, can only be used in light applications.

The pitch line is the line between the inner and outer surfaces that is neither subject to tension (like the outer surface) nor compression (like the inner). It is midway through the surfaces in film and flat belts and dependent on cross-sectional shape and size in timing and V-belts. The angular speed is inversely proportional to size, so the larger the one wheel, the less angular velocity, and vice versa. Actual pulley speeds tend to be 0.5–1% less than generally calculated because of belt slip and stretch. In timing belts, the inverse ratio teeth of the belt contributes to the exact measurement. The speed of the belt is:

Speed = Circumference based on pitch diameter × angular speed in rpm

Selection criteria

Belt drives are built under the following required conditions: speeds of and power transmitted between drive and driven unit; suitable distance between shafts; and appropriate operating conditions. The equation for power is:

power (kW) = (torque in newton-meters) × (rpm) × (2π radians)/(60 sec × 1000 W)

Factors of power adjustment include speed ratio; shaft distance (long or short); type of drive unit (electric motor, internal combustion engine); service environment (oily, wet, dusty); driven unit loads (jerky, shock, reversed); and pulley-belt arrangement (open, crossed, turned). These are found in engineering handbooks and manufacturer's literature. When corrected, the horsepower is compared to rated horsepowers of the standard belt cross sections at particular belt speeds to find a number of arrays that will perform best. Now the pulley diameters are chosen. It is generally either large diameters or large cross section that are chosen, since, as stated earlier, larger belts transmit this same power at low belt speeds as smaller belts do at high speeds. To keep the driving part at its smallest,

minimum-diameter pulleys are desired. Minimum pulley diameters are limited by the elongation of the belt's outer fibers as the belt wraps around the pulleys. Small pulleys increase this elongation, greatly reducing belt life. Minimum pulley diameters are often listed with each cross section and speed, or listed separately by belt cross section. After the cheapest diameters and belt section are chosen, the belt length is computed. If endless belts are used, the desired shaft spacing may need adjusting to accommodate standard length belts. It is often more economical to use two or more juxtaposed V-belts, rather than one larger belt.

In large speed ratios or small central distances, the angle of contact between the belt and pulley may be less than 180°. If this is the case, the drive power must be further increased, according to manufacturer's tables, and the selection process repeated. This is because power capacities are based on the standard of a 180° contact angle. Smaller contact angles mean less area for the belt to obtain traction, and thus the belt carries less power.

Belt friction

Belt drives depend on friction to operate but, if the friction is excessive, there will be waste of energy and rapid wear of the belt. Factors which affect belt friction include belt tension, contact angle and the materials from which the belt and pulleys are made.

Belt tension

Power transmission is a function of belt tension. However, also increasing with tension is stress (load) on the belt and bearings. The ideal belt is that of the lowest tension which does not slip in high loads. Belt tensions should also be adjusted to belt type, size, speed, and pulley diameters. Belt tension is determined by measuring the force to deflect the belt a given distance per inch of pulley. Timing belts need only adequate tension to keep the belt in contact with the pulley.

Belt wear

Fatigue, more so than abrasion, is the culprit for most belt problems. This wear is caused by stress from rolling around the pulleys. High belt tension; excessive slippage; adverse environmental conditions; and belt overloads caused by shock, vibration, or belt slapping all contribute to belt fatigue.

Specifications

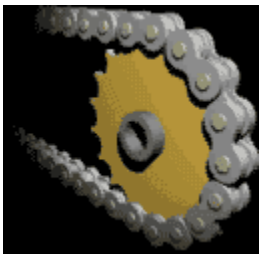
To fully specify a belt, the material, length, and cross-section size and shape are required. Timing belts, in addition, require that the size of the teeth be given. The length of the belt is the sum of the central length of the system on both sides, half the circumference of both pulleys, and the square of the sum (if crossed) or the difference (if open) of the radii. Thus, when dividing by the central distance, it can be visualized as the central distance times the height that gives the same squared value of the radius difference on, of course,

both sides. When adding to the length of either side, the length of the belt increases, in a similar manner to the Pythagorean theorem. One important concept to remember is that as D_1 gets closer to D_2 there is less of a distance (and therefore less addition of length) until its approaches zero.

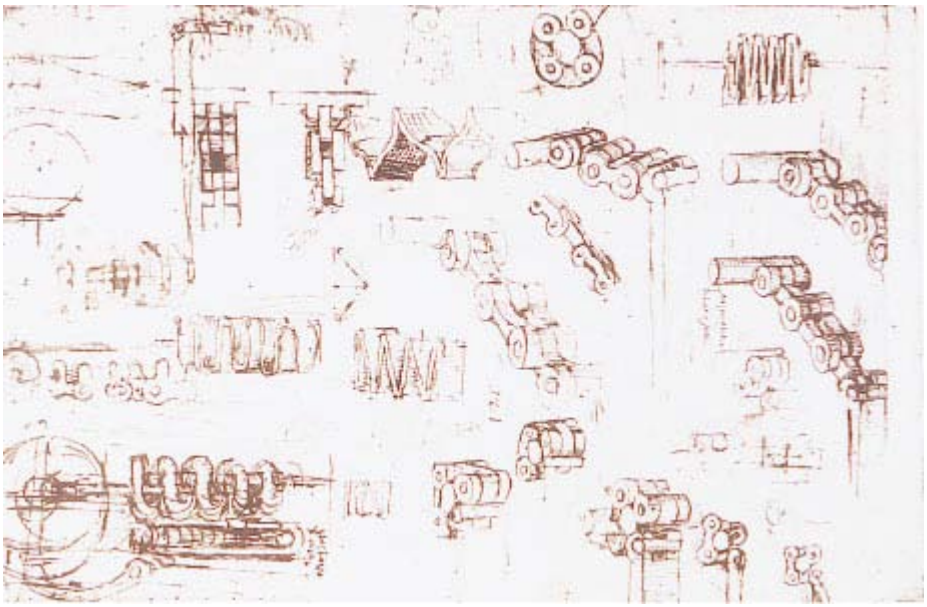
On the other hand, in a crossed belt drive the *sum* rather than the difference of radii is the basis for computation for length. So the wider the small drive increases, the belt length is higher.

Chapter 7

Roller Chain



Roller chain and sprocket



The sketch of roller chain, Leonardo da Vinci

Roller chain or **bush roller chain** is the type of chain most commonly used for transmission of mechanical power on many kinds of domestic, industrial and agricultural machinery, including conveyors, wire and tube drawing machines, printing presses, cars,

motorcycles, and simple machines like bicycles. It is a simple, reliable, and efficient means of power transmission.

Though Hans Renold is credited with inventing roller chain in 1880, sketches by Leonardo da Vinci in the 16th century show a chain with a roller bearing.

Construction of the chain

There are actually two types of links alternating in the bush roller chain. The first type is inner links, having two inner plates held together by two sleeves or bushings upon which rotate two rollers. Inner links alternate with the second type, the outer links, consisting of two outer plates held together by pins passing through the bushings of the inner links. The "bushingless" roller chain is similar in operation though not in construction; instead of separate bushings or sleeves holding the inner plates together, the plate has a tube stamped into it protruding from the hole which serves the same purpose. This has the advantage of removing one step in assembly of the chain.

The roller chain design reduces friction compared to simpler designs, resulting in higher efficiency and less wear. The original power transmission chain varieties lacked rollers and bushings, with both the inner and outer plates held by pins which directly contacted the sprocket teeth; however this configuration exhibited extremely rapid wear of both the sprocket teeth, and the plates where they pivoted on the pins. This problem was partially solved by the development of bushed chains, with the pins holding the outer plates passing through bushings or sleeves connecting the inner plates. This distributed the wear over a greater area; however the teeth of the sprockets still wore more rapidly than is desirable, from the sliding friction against the bushings. The addition of rollers surrounding the bushing sleeves of the chain and provided rolling contact with the teeth of the sprockets resulting in excellent resistance to wear of both sprockets and chain as well. There is even very low friction, as long as the chain is sufficiently lubricated. Continuous, clean, lubrication of roller chains is of primary importance for efficient operation.

Lubrication

The great majority of driving chains operate in clean environments, the wearing surfaces (ie the pins and the bushings) safe from precipitation and air-born grit, many even in a sealed environment such as an oil bath.

A few other chains run unprotected and in those cases, internally sealed roller chain manufacturers such as Tsubaki, Diamond, Morse, Renold, and Rexnord produce low-maintenance versions wherein o-rings or x-rings seal in the lubricant for life.

However, there are a few chains that have to operate in dirty conditions, and for size or operational reasons cannot be sealed. One example is the bicycle chain drive on a derailleur equipped bicycle (though cheaper hub-gear bicycles may be similarly naked to the elements). These chains will necessarily have relatively high rates of wear,

particularly when the operators are prepared to accept more friction, less efficiency, more noise and more frequent replacement as they neglect lubrication and adjustment.

Motorcycle chain lubrication

Chains operating at high speeds comparable to those on motorcycles should be used in conjunction with an oil bath. For modern motorcycles this is not applicable and most motorcycle chains run unprotected. They are subject to extreme forces and have to operate in tough conditions being exposed to rain, dirt, sand and road salt.

Motorcycle chains are part of the drive train to transmit the motor power to the back wheel. While properly lubricated chains can reach an efficiency of more 98% in the transmission, unlubricated chains will significantly decrease performance and increase chain and sprockets wear.

Two distinct types of aftermarket lubricants are available for motorcycle chains, spray on lubricants and oil drip feed systems.

- Spray lubricants may contain wax or PTFE. Whilst these lubricants use tack additives to stay on the chain they can also attract dirt and sand from the road and over time produce a grinding paste that accelerates component wear.
- Oil drip feed systems continuously lubricate the chain and use light oil that does not stick to the chain. Research has shown that oil drip feed systems provide the greatest wear protection and greatest power saving .

Scottoiler

Oil drip feed systems or **automatic motorcycle chain oilers** are often referred to as ‘Scottoilers’. Scottoiler Ltd. is a manufacturer of automatic oil drip feed systems for motorbikes. The original product is based on a vacuum system and works by gravity feed. The engine vacuum provides the power to open a valve. The oil then siphons from the reservoir by gravity and the flow rate can be adjusted by a dial opening/closing the valve aperture.

Especially in the UK the brand is on the way to become a genericized trademark.

Variants in design

If the chain is not being used for a high wear application (for instance if it is just transmitting motion from a hand operated lever to a control shaft on a machine, or a sliding door on an oven), then one of the simpler types of chain may still be used. Conversely, where extra strength but the smooth drive of a smaller pitch is required, the chain may be "siamesed"; instead of just two rows of plates on the outer sides of the chain, there may be three ("duplex"), four ("triplex"), or more rows of plates running parallel, with bushings and rollers between each adjacent pair, and the same number of

rows of teeth running in parallel on the sprockets to match. Timing chains on automotive engines, for example, typically have multiple rows of plates called strands.

Roller chain is made in several sizes, the most common American National Standards Institute (ANSI) standards being 40, 50, 60, and 80. The first digit(s) indicate the pitch of the chain in eighths of an inch, with the last digit being 0 for standard chain, 1 for lightweight chain, and 5 for bushed chain with no rollers. Thus, a bicycle chain with half inch pitch would be a #40 while a #160 sprocket would have teeth spaced 2 inches apart, etc. Metric pitches are expressed in sixteenths of an inch; thus a metric #8 chain (08B-1) would be equivalent to an ANSI #40. Most roller chain is made from plain carbon or alloy steel, but stainless steel is used in food processing machinery or other places where lubrication is a problem, and nylon or brass are occasionally seen for the same reason.

Roller chain is ordinarily hooked up using a master link (also known as a connecting link), which typically has one pin held by a horseshoe clip rather than friction fit, allowing it to be inserted or removed with simple tools. Half links (also known as offsets) are available and are used to increase the length of the chain by a single roller.

Use

- Roller chains are used in low- to mid-speed drives at around 600 to 800 feet per minute; however, at higher speeds, around 2,000 to 3,000 feet per minute, V-belts are normally used due to wear and noise issues.

- A bicycle chain is a form of roller chain. Bicycle chains may have a master link, or may require a chain tool for removal and installation. A similar but larger and thus stronger chain is used on most motorcycles although it is sometimes replaced by either a toothed belt or a shaft drive, which offer lower noise level and fewer maintenance requirements.

- In older automobile engines from the United States and other countries, roller chains would traditionally drive the camshaft(s) off the crankshaft, generating less noise than a gear drive as used in very high performance engines, and offering more durability than the timing belt frequently used on more modern engines. Many modern automobile engines still use roller chains, which are more durable than timing belts.

- Chains are also used in forklifts using hydraulic rams as a pulley to raise and lower the carriage; however, these chains are not considered roller chains, but are classified as lift or leaf chains.

- Chainsaw cutting chains superficially resemble roller chains but are more closely related to leaf chains. They are driven by projecting drive links which also serve to locate the chain onto the bar.

Sea Harrier FA.2 *ZA195* front (cold) vector thrust nozzle - the nozzle is rotated by a chain drive from an air motor

- A perhaps unusual use of a pair of motorcycle chains is in the Harrier Jump Jet, where a chain drive from an air motor is used to rotate the movable engine nozzles, allowing them to be pointed downwards for hovering flight, or to the the rear for normal forward flight, a system known as Thrust vectoring.

Wear

The effect of wear on a roller chain is to increase the pitch (spacing of the links), causing the chain to grow longer. Note that this is due to wear at the pivoting pins and bushes, not from actual stretching of the metal (as does happen to some flexible steel components such as the hand-brake cable of a motor vehicle).

With modern chains it is unusual for a chain (other than that of a bicycle) to wear until it breaks, since a worn chain leads to the rapid onset of wear on the teeth of the sprockets, with ultimate failure being the loss of all the teeth on the sprocket. The sprockets (in particular the larger of the two) suffer a grinding motion that puts a characteristic hook shape into the driven face of the teeth. (This effect is made worse by a chain improperly tensioned, but is unavoidable no matter what care is taken). The worn teeth (and chain) no longer provides smooth transmission of power and this may become evident from the noise, the vibration or (in car engines using a timing chain) the variation in ignition timing seen with a timing light. Both sprockets and chain should be replaced in these

cases, since a new chain on worn sprockets will not last long. However, in less severe cases it may be possible to save the smaller of the two sprockets, since it is always the larger one that suffers the most wear. Only in very light-weight applications such as a bicycle, or in extreme cases of improper tension, will the chain normally jump off the sprockets.

The lengthening due to wear of a chain is calculated by the following formula:

$\% = ((M - (S * P)) / (S * P)) * 100$

M = the length of a number of links measured

S = the number of links measured

P = Pitch

In industry, it is usual to monitor the movement of the chain tensioner (whether manual or automatic) or the exact length of a drive chain (one rule of thumb is to replace a roller chain which has elongated 3% on an adjustable drive or 1.5% on a fixed-center drive). A simpler method, particularly suitable for the cycle or motorcycle user, is to attempt to pull the chain away from the larger of the two sprockets. Any significant movement (eg making it possible to see through a gap) probably indicates a chain worn up to and beyond the limit. Sprocket damage will result if the problem is ignored.

Bicycle chain wear

The lightweight chain of a bicycle with derailleur gears can snap (or rather, come apart at the side-plates, since it is normal for the riveting to fail first) because the wearing pins inside are not parallel, they are barrel-shaped. Contact between the pin and the bush is not the regular line, but a point. This form of construction is necessary because the gear-changing action of this form of transmission requires the chain to both bend sideways and to twist.

Chain failure is much less of a problem on hub-geared systems (often known as "Sturmey Archer") since the parallel pins have a much bigger wearing surface in contact with the bush. The hub-gear system also allows complete enclosure, a great aid to lubrication and protection from grit.

Chain strength

The most common measure of roller chain's strength is tensile strength. Tensile strength represents how much load a chain can withstand under a one-time load before breaking. Just as important as tensile strength is a chain's fatigue strength. The critical factors in a chain's fatigue strength is the quality of steel used to manufacture the chain, the heat treatment of the chain components, the quality of the pitch hole fabrication of the linkplates, and the type of shot plus the intensity of shot peen coverage on the linkplates.

Other factors can include the thickness of the linkplates and the design (contour) of the linkplates. The rule of thumb for roller chain operating on a continuous drive is for the chain load to not exceed a mere 1/6 or 1/9 of the chain's tensile strength, depending on the type of master links used (press-fit vs. slip-fit). Roller chains operating on a continuous drive beyond these thresholds can and typically do fail prematurely via linkplate fatigue failure.

The standard minimum ultimate strength of the ANSI 29.1 steel chain is 12,500 x (pitch, in inches)^2 (pitch squared x 12,500).

Chain standards

Standards organizations (such as ANSI) maintain standards for design, dimensions, and interchangeability of transmission chains. For example, the following table shows the principal data of ANSI standard B29.1 (Precision Power Transmission Roller Chains, Attachments, and Sprockets).

NOTE: As of 1 January 2002, ANSI/AMSE B29.1 has been incorporated into ASME B29.100.

ANSI B29.1 roller chain standard sizes				
Size	**Pitch**	**Roller diameter**	**Tensile strength**	**Working load**
25	0.250 in (6.35 mm)	0.130 in (3.30 mm)	781 lb (354 kg)	140 lb (64 kg)
35	0.375 in (9.53 mm)	0.200 in (5.08 mm)	1,758 lb (797 kg)	480 lb (220 kg)
41	0.500 in (12.70 mm)	0.306 in (7.77 mm)	1,500 lb (680 kg)	500 lb (230 kg)
40	0.500 in (12.70 mm)	0.312 in (7.92 mm)	3,125 lb (1,417 kg)	810 lb (370 kg)
50	0.625 in (15.88 mm)	0.400 in (10.16 mm)	4,880 lb (2,210 kg)	1,430 lb (650 kg)
60	0.750 in (19.05 mm)	0.469 in (11.91 mm)	7,030 lb (3,190 kg)	1,980 lb (900 kg)
80	1.000 in (25.40 mm)	0.625 in (15.88 mm)	12,500 lb (5,700 kg)	3,300 lb (1,500 kg)
100	1.250 in (31.75 mm)	0.750 in (19.05 mm)	19,531 lb (8,859 kg)	5,072 lb (2,301 kg)
120	1.500 in (38.10 mm)	0.875 in (22.23 mm)	28,100 lb (12,700 kg)	6,800 lb (3,100 kg)

140	1.750 in (44.45 mm)	1.000 in (25.40 mm)	38,280 lb (17,360 kg)	9,040 lb (4,100 kg)
160	2.000 in (50.80 mm)	1.125 in (28.58 mm)	50,000 lb (23,000 kg)	11,900 lb (5,400 kg)
180	2.250 in (57.15 mm)	1.460 in (37.08 mm)	63,300 lb (28,700 kg)	13,700 lb (6,200 kg)
200	2.500 in (63.50 mm)	1.562 in (39.67 mm)	78,000 lb (35,000 kg)	16,000 lb (7,300 kg)
240	3.000 in (76.20 mm)	1.875 in (47.63 mm)	112,500 lb (51,000 kg)	22,250 lb (10,090 kg)

For mnemonic purposes, below is another presentation of key dimensions from the same standard, expressed in fractions of an inch (which was part of the thinking behind the choice of preferred numbers in the ANSI standard):

Pitch (inches)	Pitch expressed in eighths	ANSI standard chain number	Width (inches)
1/4	2/8	**2**5	1/8
3/8	3/8	**3**5	3/16
1/2	4/8	**4**1	1/4
1/2	4/8	**4**0	5/16
5/8	5/8	**5**0	3/8
3/4	6/8	**6**0	1/2
1	8/8	**8**0	5/8

Notes:
1. The pitch is the distance between roller centers. The width is the distance between the link plates (ie slightly more than the roller width to allow for clearance).
2. The right-hand digit of the standard denotes 0 = normal chain, 1 = lightweight chain, 5 = rollerless bushing chain.
3. The left-hand digit denotes the number of eighths of an inch that make up the pitch.
4. An "H" following the standard number denotes heavyweight chain. A hyphenated number following the standard number denotes double-strand (2),

triple-strand (3), and so on. Thus 60H-3 denotes number 60 heavyweight triple-strand chain.

A typical bicycle chain uses 40 series chain with a minimum tensile strength of 3,125 pounds (1,417 kg) and a working load of 810 lb (367 kg). The width of the chain is variable, and does not affect the load capacity.

Chapter 8

Variable-Frequency Drive

Small variable frequency drive

A **variable-frequency drive (VFD)** is a system for controlling the rotational speed of an alternating current (AC) electric motor by controlling the frequency of the electrical power supplied to the motor. A variable frequency drive is a specific type of adjustable-speed drive. Variable-frequency drives are also known as adjustable-frequency drives (AFD), variable-speed drives (VSD), AC drives, microdrives or inverter drives. Since the voltage is varied along with frequency, these are sometimes also called **VVVF** (variable voltage variable frequency) drives.

Variable-frequency drives are widely used. In ventilation systems for large buildings, variable-frequency motors on fans save energy by allowing the volume of air moved to match the system demand. They are also used on pumps, elevator, conveyor and machine tool drives.

VFD types

All VFDs use their output devices (IGBTs, transistors, thyristors) only as switches, turning them only on or off. Using a linear device such as a transistor in its linear mode is impractical for a VFD drive, since the power dissipated in the drive devices would be about as much as the power delivered to the load.

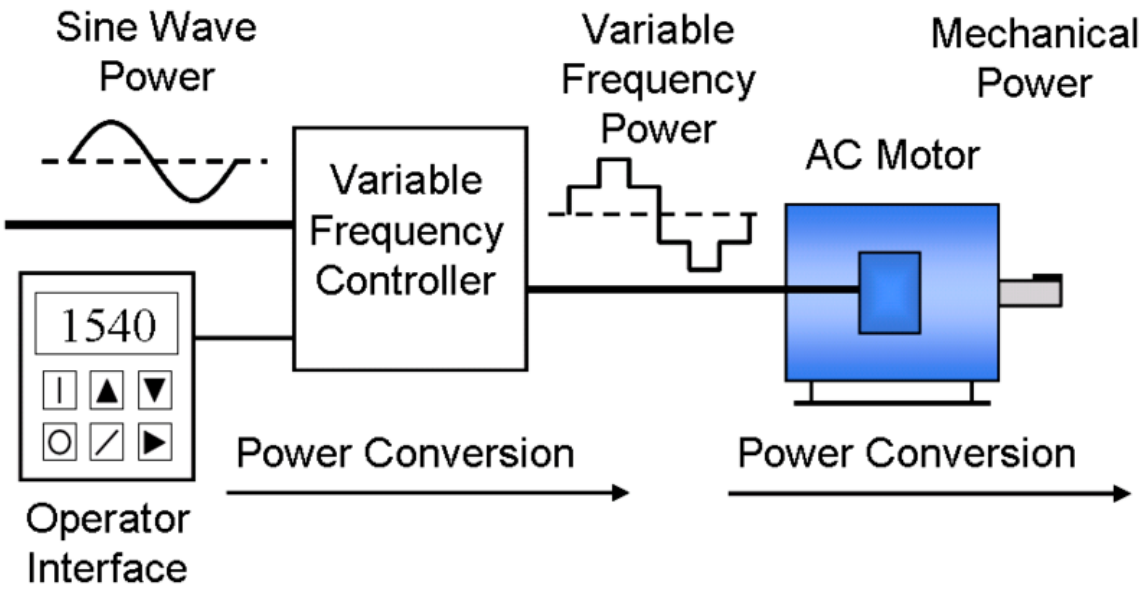
Drives can be classified as:

- Constant voltage
- Constant current
- Cycloconverter

In a constant voltage converter, the intermediate DC link voltage remains approximately constant during each output cycle. In constant current drives, a large inductor is placed between the input rectifier and the output bridge, so the current delivered is nearly constant. A cycloconverter has no input rectifier or DC link and instead connects each output terminal to the appropriate input phase.

The most common type of packaged VF drive is the constant-voltage type, using pulse width modulation to control both the frequency and effective voltage applied to the motor load.

VFD system description



VFD system

A variable frequency drive system generally consists of an AC motor, a controller and an operator interface.

VFD motor

The motor used in a VFD system is usually a three-phase induction motor. Some types of single-phase motors can be used, but three-phase motors are usually preferred. Various types of synchronous motors offer advantages in some situations, but induction motors are suitable for most purposes and are generally the most economical choice. Motors that are designed for fixed-speed operation are often used. Certain enhancements to the standard motor designs offer higher reliability and better VFD performance, such as MG-31 rated motors.

VFD controller

Variable frequency drive controllers are solid state electronic power conversion devices. The usual design first converts AC input power to DC intermediate power using a rectifier or converter bridge. The rectifier is usually a three-phase, full-wave-diode bridge. The DC intermediate power is then converted to quasi-sinusoidal AC power using an inverter switching circuit. The inverter circuit is probably the most important section of the VFD, changing DC energy into three channels of AC energy that can be used by an AC motor. These units provide improved power factor, less harmonic distortion, and low sensitivity to the incoming phase sequencing than older phase controlled converter VFD's. Since incoming power is converted to DC, many units will accept single-phase as

well as three-phase input power (acting as a phase converter as well as a speed controller); however the unit must be derated when using single phase input as only part of the rectifier bridge is carrying the connected load.

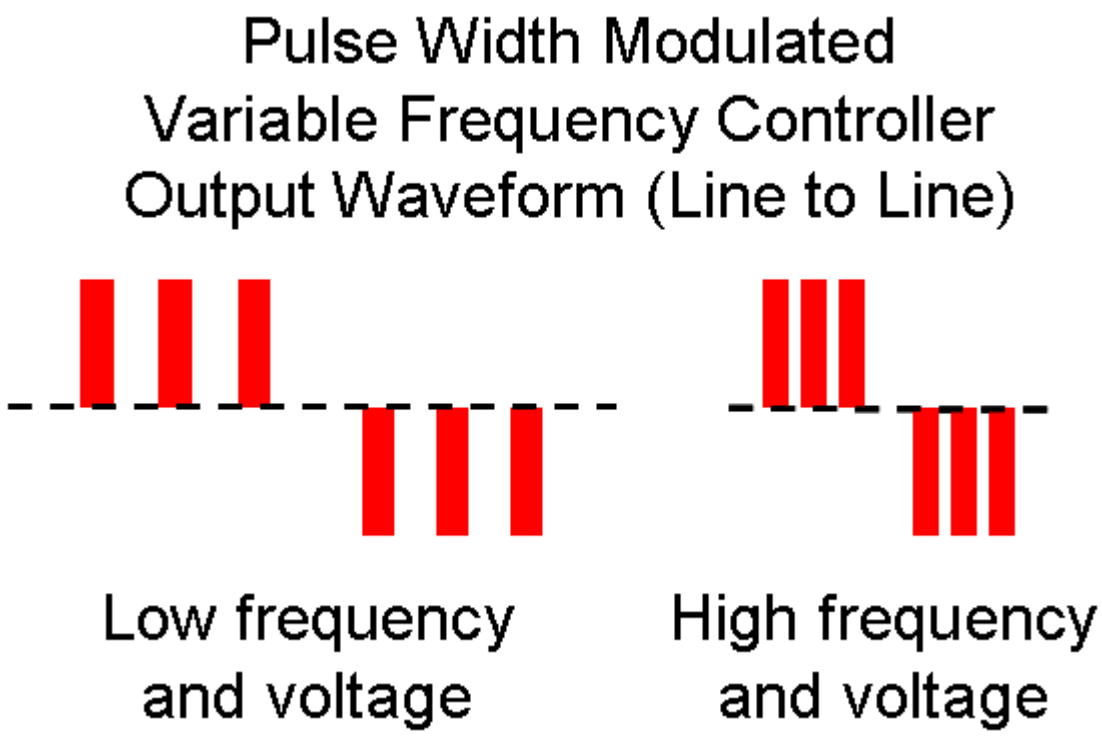
As new types of semiconductor switches have been introduced, these have promptly been applied to inverter circuits at all voltage and current ratings for which suitable devices are available. Introduced in the 1980s, the insulated-gate bipolar transistor (IGBT) became the device used in most VFD inverter circuits in the first decade of the 21st century.

AC motor characteristics require the applied voltage to be proportionally adjusted whenever the frequency is changed in order to deliver the rated torque. For example, if a motor is designed to operate at 460 volts at 60 Hz, the applied voltage must be reduced to 230 volts when the frequency is reduced to 30 Hz. Thus the ratio of volts per hertz must be regulated to a constant value (460/60 = 7.67 V/Hz in this case). For optimum performance, some further voltage adjustment may be necessary especially at low speeds, but constant volts per hertz is the general rule. This ratio can be changed in order to change the torque delivered by the motor.

In addition to this simple volts per hertz control more advanced control methods such as vector control and direct torque control (DTC) exist. These methods adjust the motor voltage in such a way that the magnetic flux and mechanical torque of the motor can be precisely controlled.

The usual method used to achieve variable motor voltage is pulse-width modulation (PWM). With PWM voltage control, the inverter switches are used to construct a quasi-sinusoidal output waveform by a series of narrow voltage pulses with pseudosinusoidal varying pulse durations.

Operation of the motors above rated name plate speed (base speed) is possible, but is limited to conditions that do not require more power than nameplate rating of the motor. This is sometimes called "field weakening" and, for AC motors, means operating at less than rated volts/hertz and above rated name plate speed. Permanent magnet synchronous motors have quite limited field weakening speed range due to the constant magnet flux linkage. Wound rotor synchronous motors and induction motors have much wider speed range. For example, a 100 hp, 460 V, 60 Hz, 1775 RPM (4 pole) induction motor supplied with 460 V, 75 Hz (6.134 V/Hz), would be limited to 60/75 = 80% torque at 125% speed (2218.75 RPM) = 100% power. At higher speeds the induction motor torque has to be limited further due to the lowering of the breakaway torque of the motor. Thus rated power can be typically produced only up to 130...150 % of the rated name plate speed. Wound rotor synchronous motors can be run even higher speeds. In rolling mill drives often 200...300 % of the base speed is used. Naturally the mechanical strength of the rotor and lifetime of the bearings is also limiting the maximum speed of the motor. It is recommended to consult the motor manufacturer if more than 150 % speed is required by the application.



PWM VFD Output Voltage Waveform

An embedded microprocessor governs the overall operation of the VFD controller. The main microprocessor programming is in firmware that is inaccessible to the VFD user. However, some degree of configuration programming and parameter adjustment is usually provided so that the user can customize the VFD controller to suit specific motor and driven equipment requirements.

VFD operator interface

The operator interface provides a means for an operator to start and stop the motor and adjust the operating speed. Additional operator control functions might include reversing and switching between manual speed adjustment and automatic control from an external process control signal. The operator interface often includes an alphanumeric display and/or indication lights and meters to provide information about the operation of the drive. An operator interface keypad and display unit is often provided on the front of the VFD controller as shown in the photograph above. The keypad display can often be cable-connected and mounted a short distance from the VFD controller. Most are also provided with input and output (I/O) terminals for connecting pushbuttons, switches and other operator interface devices or control signals. A serial communications port is also often available to allow the VFD to be configured, adjusted, monitored and controlled using a computer.

VFD operation

When an induction motor is connected to a full voltage supply, it draws several times (up to about 6 times) its rated current. As the load accelerates, the available torque usually drops a little and then rises to a peak while the current remains very high until the motor approaches full speed.

By contrast, when a VFD starts a motor, it initially applies a low frequency and voltage to the motor. The starting frequency is typically 2 Hz or less. Thus starting at such a low frequency avoids the high inrush current that occurs when a motor is started by simply applying the utility (mains) voltage by turning on a switch. After the start of the VFD, the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load without drawing excessive current. This starting method typically allows a motor to develop 150% of its rated torque while the VFD is drawing less than 50% of its rated current from the mains in the low speed range. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed. Note, however, that cooling of the motor is usually not good in the low speed range. Thus running at low speeds even with rated torque for long periods is not possible due to overheating of the motor. If continuous operation with high torque is required in low speeds an external fan is usually needed. The manufacturer of the motor and/or the VFD should specify the cooling requirements for this mode of operation.

In principle, the current on the motor side is in direct proportion of the torque that is generated and the voltage on the motor is in direct proportion of the actual speed, while on the network side, the voltage is constant, thus the current on line side is in direct proportion of the power drawn by the motor, that is U.I or C.N where C is torque and N the speed of the motor (we shall consider losses as well, neglected in this explanation).

(1) n stands for network (grid) and m for motor
(2) C stands for torque [Nm], U for voltage [V], I for current [A], and N for speed [rad/s]
We neglect losses for the moment :
Un.In = Um.Im (same power drawn from network and from motor)
Um.Im = Cm.Nm (motor mechanical power = motor electrical power)
Given Un is a constant (network voltage) we conclude : In = Cm.Nm/Un That is "line current (network) is in direct proportion of motor power".

With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. A small amount of braking torque is available to help decelerate the load a little faster than it would stop if the motor were simply switched off and allowed to coast. Additional braking torque can be obtained by adding a braking circuit (resistor controlled by a transistor) to dissipate the braking energy. With 4-quadrants rectifiers (active-front-end), the VFD is able to brake the load by applying a reverse torque and reverting the energy back to the network.

Power line harmonics

While PWM allows for nearly sinusoidal currents to be applied to a motor load, the diode rectifier of the VFD takes roughly square-wave current pulses out of the AC grid, creating harmonic distortion in the power line voltage. When the VFD load size is small and the available utility power is large, the effects of VFD systems slicing small chunks out of AC grid generally go unnoticed. Further, in low voltage networks the harmonics caused by single phase equipment such as computers and TVs are such that they are partially cancelled by three-phase diode bridge harmonics.

However, when either a large number of low-current VFDs, or just a few very large-load VFDs are used, they can have a cumulative negative impact on the AC voltages available to other utility customers in the same grid.

When the utility voltage becomes misshapen and distorted the losses in other loads such as normal AC motors are increased. This may in the worst case lead to overheating and shorter operation life. Also substation transformers and compensation capacitors are affected, the latter especially if resonances are aroused by the harmonics.

In order to limit the voltage distortion the owner of the VFDs may be required to install filtering equipment to smooth out the irregular waveform. Alternately, the utility may choose to install filtering equipment of its own at substations affected by the large amount of VFD equipment being used. In high power installations decrease of the harmonics can be obtained by supplying the VSDs from transformers that have different phase shift.

Further, it is possible to use instead of the diode rectifier a similar transistor circuit that is used to control the motor. This kind of rectifier is called active infeed converter in IEC standards. However, manufacturers call it by several names such as active rectifier, ISU (IGBT Supply Unit), AFE (Active Front End) or four quadrant rectifier. With PWM control of the transistors and filter inductors in the supply lines the AC current can be made nearly sinusoidal. Even better attenuation of the harmonics can be obtained by using an LCL (inductor-capacitor-inductor) filter instead of single three-phase filter inductor.

Additional advantage of the active infeed converter over the diode bridge is its ability to feed back the energy from the DC side to the AC grid. Thus no braking resistor is needed and the efficiency of the drive is improved if the drive is frequently required to brake the motor.

Application considerations

The output voltage of a PWM VFD consists of a train of pulses switched at the carrier frequency. Because of the rapid rise time of these pulses, transmission line effects of the cable between the drive and motor must be considered. Since the transmission-line impedance of the cable and motor are different, pulses tend to reflect back from the motor

terminals into the cable. The resulting voltages can produce up to twice the rated line voltage for long cable runs, putting high stress on the cable and motor winding and eventual insulation failure. Increasing the cable or motor size/type for long runs and 480v or 600v motors will help offset the stresses imposed upon the equipment due to the VFD (modern 230v single phase motors not effected). At 460 V, the maximum recommended cable distances between VFDs and motors can vary by a factor of 2.5:1. The longer cables distances are allowed at the lower Carrier Switching Frequencies (CSF) of 2.5 kHz. The lower CSF can produce audible noise at the motors. For applications requiring long motor cables VSD manufacturers usually offer du/dt filters that decrease the steepness of the pulses. For very long cables or old motors with insufficient winding insulation more efficient sinus filter is recommended. Expect the older motor's life to shorten. Purchase VFD rated motors for the application.

Further, the rapid rise time of the pulses may cause trouble with the motor bearings. The stray capacitance of the windings provide paths for high frequency currents that close through the bearings. If the voltage between the shaft and the shield of the motor exceeds few volts the stored charge is discharged as a small spark. Repeated sparking causes erosion in the bearing surface that can be seen as fluting pattern. In order to prevent sparking the motor cable should provide a low impedance return path from the motor frame back to the inverter. Thus it is essential to use a cable designed to be used with VSDs.

In big motors a slip ring with brush can be used to provide a bypass path for the bearing currents. Alternatively isolated bearings can be used.

The 2.5 kHz and 5 kHz CSFs cause fewer motor bearing problems than the 20 kHz CSFs. Shorter cables are recommended at the higher CSF of 20 kHz. The minimum CSF for synchronize tracking of multiple conveyors is 8 kHz.

The high frequency current ripple in the motor cables may also cause interference with other cabling in the building. This is another reason to use a motor cable designed for VSDs that has a symmetrical three-phase structure and good shielding. Further, it is highly recommended to route the motor cables as far away from signal cables as possible.

Available VFD power ratings

Variable frequency drives are available with voltage and current ratings to match the majority of 3-phase motors that are manufactured for operation from utility (mains) power. VFD controllers designed to operate at 111 V to 690 V are often classified as low voltage units. Low voltage units are typically designed for use with motors rated to deliver 0.2 kW or 1/4 horsepower (hp) up to several megawatts. For example, the largest ABB ACS800 single drives are rated for 5.6 MW . Medium voltage VFD controllers are designed to operate at 2,400/4,162 V (60 Hz), 3,000 V (50 Hz) or up to 10 kV. In some applications a step up transformer is placed between a low voltage drive and a medium voltage load. Medium voltage units are typically designed for use with motors rated to

deliver 375 kW or 500 hp and above. Medium voltage drives rated above 7 kV and 5,000 or 10,000 hp should probably be considered to be one-of-a-kind (one-off) designs.

Medium voltage drives are generally rated amongst the following voltages : 2,3 KV - 3,3 Kv - 4 Kv - 6 Kv - 11 Kv
The in-between voltages are generally possible as well. The power of MV drives is generally in the range of 0,3 to 100 MW however involving a range a several different type of drives with different technologies.

Dynamic braking

Using the motor as a generator to absorb energy from the system is called dynamic braking. Dynamic braking stops the system more quickly than coasting. Since dynamic braking requires relative motion of the motor's parts, it becomes less effective at low speed and cannot be used to hold a load at a stopped position. During normal braking of an electric motor the electrical energy produced by the motor is dissipated as heat inside of the rotor, which increases the likelihood of damage and eventual failure. Therefore, some systems transfer this energy to an outside bank of resistors. Cooling fans may be used to protect the resistors from damage. Modern systems have thermal monitoring, so if the temperature of the bank becomes excessive, it will be switched off.

Regenerative variable-frequency drives

Regenerative AC drives have the capacity to recover the braking energy of an overhauling load and return it to the power system.

Line regenerative variable frequency drives, showing capacitors(top cylinders)and inductors attached which filter the regenerated power.

Cycloconverters and current-source inverters inherently allow return of energy from the load to the line; voltage-source inverters require an additional converter to return energy to the supply.

Regeneration is only useful in variable-frequency drives where the value of the recovered energy is large compared to the extra cost of a regenerative system, and if the system requires frequent braking and starting. An example would be use in conveyor belt during manufacturing where it should stop for every few minutes, so that the parts can be assembled correctly and moves on. Another example is a crane, where the hoist motor stops and reverses frequently, and braking is required to slow the load during lowering.

Regenerative variable-frequency drives are widely used where speed control of overhauling loads is required.

Brushless DC motor drives

Much of the same logic contained in large, powerful VFDs is also embedded in small brushless DC motors such as those commonly used in computer fans. In this case, the chopper usually converts a low DC voltage (such as 12 volts) to the three-phase current used to drive the electromagnets that turn the permanent magnet rotor.

Chapter 9

Line Shaft

Four wool spinning machines driven by belts from an overhead lineshaft (Leipzig, Germany, circa 1925)

A **line shaft** is a power transmission system used extensively during the Industrial Revolution. Prior to the widespread use of electric motors small enough to be connected directly to each piece of machinery, line shafting was used to distribute power from a large central power source to machinery throughout an industrial complex. The central power source could be a water wheel or turbine, animal power, a stationary steam engine,

a steam traction engine, a portable engine, or, in later years, a single large electric motor. Power was distributed from the shaft to the machinery by a system of belts,and pulleys.

History

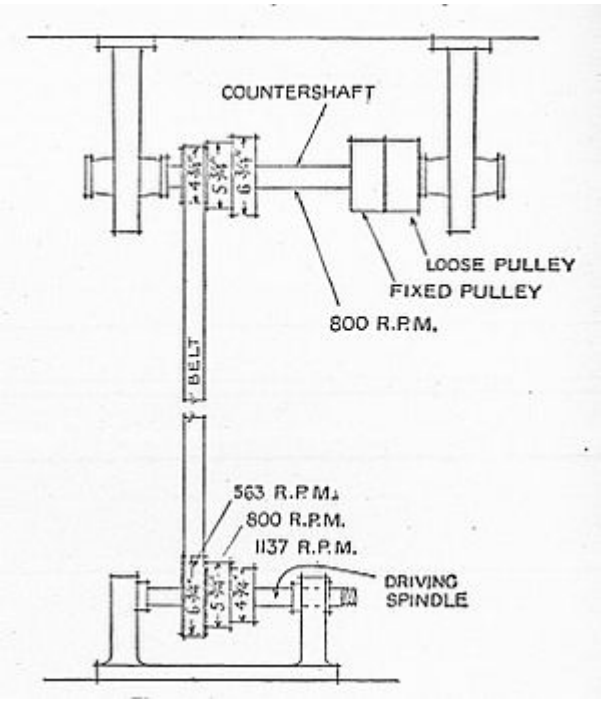
Early version of line shafts date back into the 18th century, but truly came of age in the early 19th century industrialization and manufacturing. Line shafts were widely used in manufacturing, woodworking shops, machine shops, saw mills and grist mills.

Flat belt drive systems became popular in the UK from the 1870s, with the firms of J E Wood and W & J Galloway & Sons prominent in their introduction. Both of these firms manufactured stationary steam engines and the continuing demand for more power and reliability could be met not merely by improved engine technology but also improved methods of transferring power from the engines to the looms and similar machinery which they were intended to service. The use of flat belts was already common in the US but rare in Britain until this time. The advantages included less noise and less wasted energy in the friction losses inherent in the previously common drive shafts and their associated gearing. Also, maintenance was simpler and cheaper, and it was a more convenient method for the arrangement of power drives such that if one part were to fail then it would not cause loss of power to all sections of a factory or mill. These systems were in turn superseded in popularity by rope drive methods.

Line shafting fell out of favor in the early-to-mid 20th century with the widespread availability of electrical power and availability of compact electric motors. Such independent motors are far less maintenance intensive than maintaining a line shaft system. Those systems in place tended to be converted to power from a large internal combustion engine or large electric motor. Some systems were broken up with separate motors driving different parts of what was one system. Most systems were out of service by the mid-20th century and relatively few remain in the 21st century, even fewer in their original location and configuration.

Most paper machines used steam turbine -powered line shafts until the 1980s, since then many have been replaced with sectional electric drives.

Operation



Variable speed belt drive for a lathe. The fixed pulley on the upper shaft is driven at constant speed by a belt from the power source. The loose pulley ('idler') allows the machine to be stopped in isolation – necessary for changing speed. The stepped pulleys (left) provide three drive speeds for the machine tool (not shown), depending on which pair of pulleys is connected by the belt.

A typical line shaft would be suspended from the ceiling of one area and would run the length of that area. One pulley on the shaft would receive the power from the a parent line shaft elsewhere in the building. The other pulleys would supply power to pulleys on each individual machine or to subsequent line shafts. In manufacturing where there were a large number of machines performing the same tasks, the design of the system was fairly regular and repeated. In other applications such as machine and wood shops where there was a variety of machines with different orientations and power requirements, the system would appear erratic and inconsistent with many different shafting directions and pulley sizes. Shafts were usually horizontal and overhead but occasionally were vertical and could be underground. Shafts were usually rigid steel, made up of several parts bolted together at flanges. The shafts were suspended by hangers with bearings at certain intervals of length. The distance depended on the weight of the shaft and the number of pulleys. The shafts had to be kept aligned or the stress would overheat the bearings and could break the shaft. The bearings were usually friction type and had to be kept lubricated.

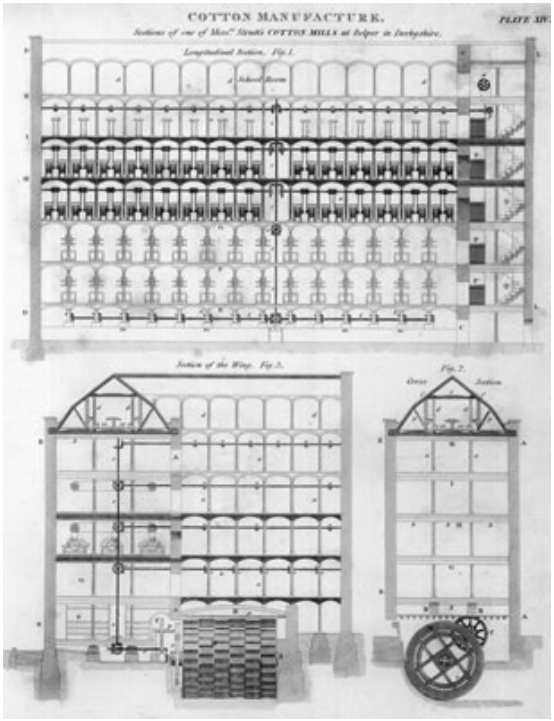
In the earliest applications power was transmitted between pulleys using loops of rope on grooved pulleys. This method is extremely rare today, dating mostly from the 18th century. Flat belts on flat pulleys or drums were the most common method during the

19th and early 20th century. The belts were generally tanned leather or cotton duck impregnated with rubber. Leather belts were fastened in loops with rawhide or wire lacing, lap joints and glue, or one of several types of steel fasteners. Cotton duck belts usually used metal fasteners or were melted together with heat. The leather belts were run with the hair side against the pulleys for best traction. The belts needed periodic cleaning and conditioning to keep them in good condition. Belts were often twisted 180 degrees per leg and reversed on the receiving pulley to cause the second shaft to rotate in the opposite direction.

Pulleys were constructed of wood, iron, steel or a combination thereof. Varying sizes of pulleys were used in conjunction to change the speed of rotation. For example a 40" pulley at 100 RPM would turn a 20" pulley at 200 RPM. Pulleys solidly attached to the shaft could be combined with adjacent pulleys that turned freely on the shaft (idlers). In this configuration the belt could be maneuvered onto the idler to stop power transmission or onto the solid pulley to convey the power. This arrangement was often used near machines to provide a means of shutting the machine off when not in use. Usually at the last belt feeding power to a machine, a pair of stepped pulleys could be used to give a variety of speed settings for the machine.

Occasionally gears were used between shafts to change speed rather than belts and different sized pulleys, but this seems to have been relatively uncommon.

Early Examples



Jedediah Strutt, North Mill at Belper in 1819, showing vertical shaft leading from the 18 feet (5.5 m) waterwheel, to horizontal drive shafts running the length of each floor on each floor

In an early example, Jedediah Strutt's water-powered cotton mill, North Mill in Belper, built in 1776, all the power to operate the machinery came from a 18 feet (5.5 m) water wheel.

Preservation

Original Systems

- East Broad Top Railroad and Coal Company. Rockhill Furnace, PA (inoperable wood shop, blacksmiths shop, foundry)
- Longleaf Lumber Company/Southern Forest Heritage Museum, Longleaf, LA (partially operable - machine tools, sawmill)
- Sierra Railroad Shops/Railtown 1897 State Historic Park, Jamestown, CA (operable - machine tools, blachsmith shop)
- Empire Mine State Park machine Shop, Grass Valley, CA (??? - machine tools)
- Hagley Museum, Wilmington, DE
- Stott Park Bobbin Mill, Cumbria, England (???)
- Mingus Mill, Great Smokey Mountains National Park, SC (partially operable - grain mill)
- Hanford Mills Museum, East Meredith, NY (???)
- Slater Mill Historic Site, Pawtucket, RI (???)
- Thomas Edison National Historical Park, West Orange, NJ (??? - Machine Tools)
- W J Doran Company, Waupaca, WI, (fully operational - machine tools)
- Shelsley Watermill, Shelsley Walsh, Worcester, UK (partially operable - grain mill)
- Cruiser Olympia, Philadelphia PA (operational machine shop)

Reconstructed or Demonstration Systems

- Smithsonian Institution, Arts and Industries Building, Washington DC (machine tools)
- White River Valley Antique Association, Enora, IN (machine and woodworking tools)
- Denton Farmpark, Denton, NC (machine tools)
- Cincinnati History Museum, Cincinnati, OH (machine tools)
- Henry Ford Museum and Greenfield Village, Dearborn, MI (machine tools)
- Molly Kathleen Mine, Clear Creek, CO (sawmill)
- Boott Mills, Lowell, MA (power cotton looms)
- Silver Dollar City, Branson, MO (woodworking tools and bakery machinery)
- Tuckahoe Steam & Gas Association, Easton, MD (machine tools)

Chapter 10

Adjustable-Speed Drive

Adjustable speed drive (ASD) or variable-speed drive (VSD) describes equipment used to control the speed of machinery. Many industrial processes such as assembly lines must operate at different speeds for different products. Where process conditions demand adjustment of flow from a pump or fan, varying the speed of the drive may save energy compared with other techniques for flow control.

Where speeds may be selected from several different pre-set ranges, usually the drive is said to be "adjustable" speed. If the output speed can be changed without steps over a range, the drive is usually referred to as "variable speed".

Adjustable and variable speed drives may be purely mechanical (termed 'Variators'), electromechanical, hydraulic, or electronic.

Line regenerative variable frequency drives, showing capacitors(top cylinders)and inductors attached which filter the regenerated power.

Fixed speeds of electric motors

Alternating-current electric motors run at speeds closely determined by the number of poles in the motor and the frequency of the alternating current supply. This is unlike the steam engine, which can be made to run over a range of speeds by adjusting the timing and duration of valves admitting steam to the cylinder.

AC motors can be made with several sets of poles, which can be chosen to give one of several different speeds (say, 720/1800 RPM for a 60 Hz motor). The number of different speeds available is limited by the expense of providing multiple sets of windings. If many different speeds or continuously variable speeds are required, other methods are required.

Direct-current motors allow for changes of speed by adjusting the shunt field current. Another way of changing speed of a direct current motor is to change the voltage applied to the armature.

An adjustable speed drive might consist of an electric motor and controller that is used to adjust the motor's operating speed. The combination of a constant-speed motor and a steplessly adjustable mechanical speed-changing device might also be called an adjustable speed drive. Electronic variable frequency drives are rapidly making older technology redundant.

Reasons for using adjustable speed drives

Process control and energy conservation are the two primary reasons for using an adjustable speed drive. Historically, adjustable speed drives were developed for process control, but energy conservation has emerged as an equally important objective.

Adjusting speed as a means of controlling a process

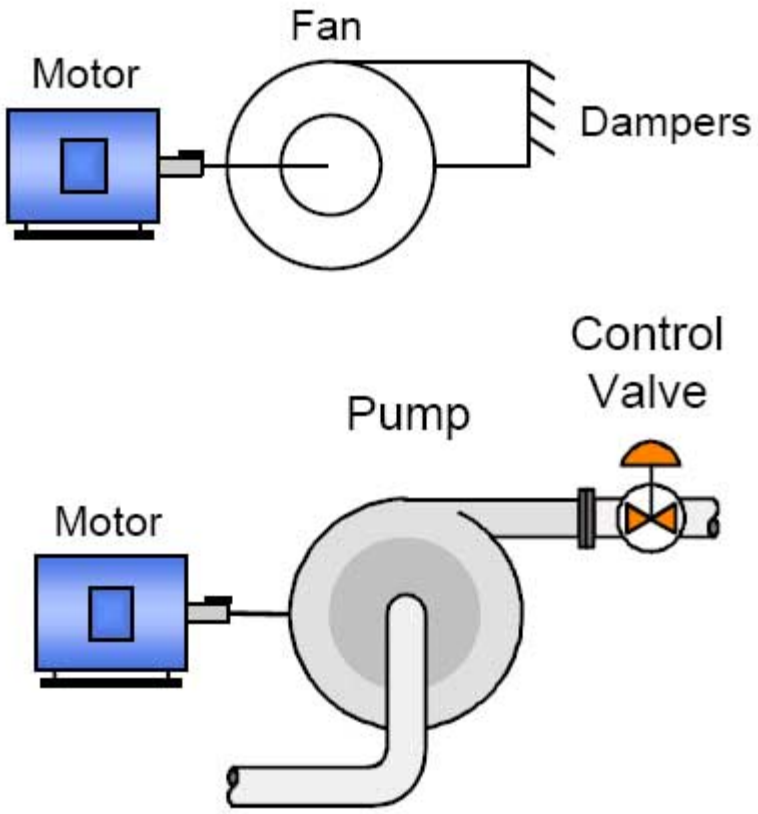
The following are process control benefits that might be provided by an adjustable speed drive:

- Smoother operation
- Acceleration control
- Different operating speed for each process recipe
- Compensate for changing process variables
- Allow slow operation for setup purposes
- Adjust the rate of production
- Allow accurate positioning
- Control torque or tension

Example

An adjustable speed drive can often provide smoother operation compared to an alternative fixed speed mode of operation. For example, in a sewage lift station sewage usually flows through sewer pipes under the force of gravity to a wet well location. From there it is pumped up to a treatment process. When fixed speed pumps are used, the pumps are set to start when the level of the liquid in the wet well reaches some high point and stop when the level has been reduced to a low point. Cycling the pumps on and off results in frequent high surges of electric current to start the motors resulting in

electromagnetic and thermal stresses in the motors and power control equipment, the pumps and pipes are subjected to mechanical and hydraulic stresses, and the sewage treatment process is forced to accommodate surges in the flow of sewage through the process. When adjustable speed drives are used, the pumps operate continuously at a speed that increases as the wet well level increases. This matches the outflow to the average inflow and provides a much smoother operation of the process.



Saving energy by using adjustable speed drives

An adjustable speed drive often uses less energy than an alternative fixed speed mode of operation. Fans and pumps are the most common energy saving applications. When a fan is driven by a fixed speed motor, the airflow may sometimes be higher than it needs to be. Airflow can be regulated by using a damper to restrict the flow, but it is more efficient to regulate the airflow by regulating the speed of the motor. It follows from the affinity laws that reducing fan speed to 50% results in a power consumption drop to 12.5%.

Types of adjustable speed drives

Speed adjustment techniques have been used in transmitting mechanical power to machinery since the earliest use of powered machinery. Before electric motors were

invented, mechanical speed changers were used to control the mechanical power provided by water wheels and steam engines. When electric motors came into use, means of controlling their speed were developed almost immediately. Today, various types of mechanical drives, hydraulic drives and electric drives compete with one another in the industrial drives market.

Mechanical adjustable speed drives

There are two types of mechanical drives, variable pitch drives and traction drives.

Variable pitch drives are pulley and belt drives in which the pitch diameter of one or both pulleys can be adjusted.

Traction drives transmit power through metal rollers running against mating metal rollers. The input/output speed ratio is adjusted by moving the rollers to change the diameters of the contact path. Many different roller shapes and mechanical designs have been used.

Hydraulic adjustable speed drives

There are three types of hydraulic drives, those are : hydrostatic drives, hydrodynamic drives and hydroviscous drives.

A **hydrostatic drive** consists of a hydraulic pump and a hydraulic motor. Since positive displacement pumps and motors are used, one revolution of the pump or motor corresponds to a set volume of fluid flow that is determined by the displacement regardless of speed or torque. Speed is regulated by regulating the fluid flow with a valve or by changing the displacement of the pump or motor. Many different design variations have been used. A swash plate drive employs an axial piston pump and/or motor in which the swash plate angle can be changed to adjust the displacement and thus adjust the speed.

Hydrodynamic drives or fluid couplings use oil to transmit torque between an impeller on the constant-speed input shaft and a rotor on the adjustable-speed output shaft. The torque converter in the automatic transmission of a car is a hydrodynamic drive.

A **hydroviscous drive** consists of one or more discs or connected to the input shaft pressed against a similar disc or discs connected to the output shaft. Torque is transmitted from the input shaft to the output shaft through an oil film between the discs. The transmitted torque is proportional to the pressure exerted by a hydraulic cylinder that presses the discs together.

Continuously variable transmission (CVT)

Mechanical and hydraulic adjustable speed drives are usually called transmissions or continuously variable transmissions when they are used in vehicles, farm equipment and some other types of equipment.

Electric adjustable speed drives

There are three general categories of electric drives: DC motor drives, eddy current drives and AC motor drives. Each of these general types can be further divided into numerous variations. Electric drives generally include both an electric motor and a speed control unit or system. The term *drive* is often applied to the controller without the motor. In the early days of electric drive technology, electromechanical control systems were used. Later, electronic controllers were designed using various types of vacuum tubes. As suitable solid state electronic components became available, new controller designs incorporated the latest electronic technology.

DC drives

DC drives are DC motor speed control systems. Since the speed of a DC motor is directly proportional to armature voltage and inversely proportional to motor flux (which is a function of field current), either armature voltage or field current can be used to control speed. Several types of DC motors are described in the electric motor article. The electric motor article also describes electronic speed controls used with various types of DC motors.

Eddy current drives

An eddy current drive consists of a fixed speed motor and an eddy current clutch. The clutch contains a fixed speed rotor and an adjustable speed rotor separated by a small air gap. A direct current in a field coil produces a magnetic field that determines the torque transmitted from the input rotor to the output rotor. The controller provides closed loop speed regulation by varying clutch current, only allowing the clutch to transmit enough torque to operate at the desired speed. Speed feedback is typically provided via an integral AC tachometer.

Eddy current drives are a type of *slip controlled drive*. Slip controlled drives are generally less efficient than other types of drives. The motor develops the torque required by the load and operates at full speed. The output shaft transmits the same torque to the load, but turns at a slower speed. Since power is proportional to torque multiplied by speed, the input power is proportional to motor speed times operating torque while the output power is output speed times operating torque. The difference between the motor speed and the output speed is called the *slip speed*. Power proportional to the slip speed times operating torque is dissipated as heat in the clutch.

AC drives

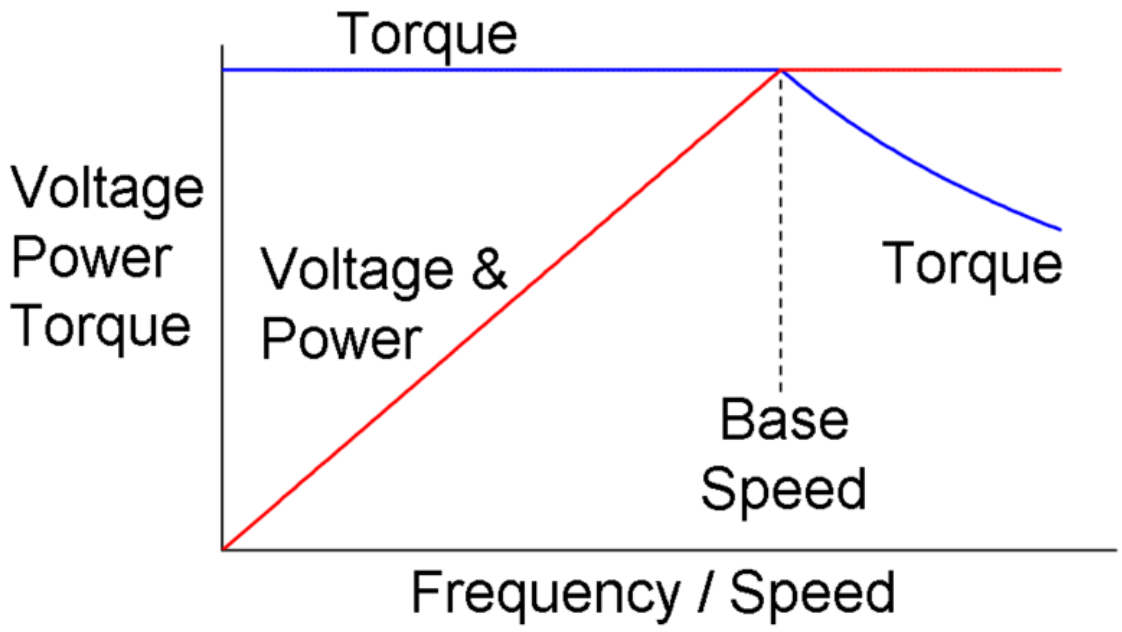
AC drives are AC motor speed control systems.

Slip controlled drives control the speed of an induction motor by increasing a motor's slip, either by reducing the voltage applied to the motor, or increasing the resistance of the rotor windings. Because they are generally less efficient than other types of drives,

slip controlled drives have lost popularity and have recently been used only in special situations.

In larger ratings (more than a few kilowatts), a wound-rotor motor has its rotor connected to a converter that returns energy to the power system, converting it from low slip frequency to the line freqeuncy. This reclaims the energy that would otherwise be wasted in rotor circuit resistors. These are called "slip energy recovery drives" and are used on such applications as forced-draft blowers for boilers. An electromechanical version using a rectifier, DC motor and AC generator is called a *Kramer drive*.

Adjustable-frequency drives (AFD) control the speed of either an induction motor or a synchronous motor by adjusting the frequency of the power supplied to the motor. Adjustable frequency drives are also known as variable-frequency drives (VFD).



When changing the frequency of the power supplied to an AC motor, the ratio of the applied voltage to the applied frequency (V/Hz) is generally maintained at a constant value between the minimum and maximum operating frequencies. Operation at a constant voltage (reduced V/Hz) above a given frequency provides reduced torque capability and constant power capability above that frequency. The frequency or speed at which constant-voltage operation begins is called the *base* frequency or speed. Whether the applied voltage is regulated directly or indirectly, the V/Hz tends to follow the general pattern described for the performance described. The variable-frequency drive article

provides additional information on electronic speed controls used with various types of AC motors.

Regenerative variable-Frequency drives

Regenerative AC drives are a type of AC drive and have the capacity to recover the braking energy of an overhauling load and return it to the power system.

Chapter 11

Fluid Coupling

A **fluid coupling** is a hydrodynamic device used to transmit rotating mechanical power. It has been used in automobile transmissions as an alternative to a mechanical clutch. It also has widespread application in marine and industrial machine drives, where variable speed operation and/or controlled start-up without shock loading of the power transmission system is essential.

History

The **fluid coupling** originates from the work of Dr. Hermann Föttinger, who was the chief designer at the AG Vulcan Works in Stettin. His patents from 1905 covered both fluid couplings and torque converters.

In 1930 Harold Sinclair, working with the Daimler company, devised a transmission system using a fluid coupling and planetary gearing for buses in an attempt to mitigate the lurching he had experienced while riding on London buses during the 1920s.

In 1939 General Motors Corporation introduced Hydramatic drive, the first fully automatic automotive transmission system installed in a mass produced automobile. The Hydramatic employed a fluid coupling.

The first Diesel locomotives using fluid couplings were also produced in the 1930s

Overview

A fluid coupling consists of three components, plus the hydraulic fluid:

- The housing, also known as the *shell* (which must have an oil tight seal around the drive shafts), contains the fluid and turbines.
- Two turbines (fan like components):
    - One connected to the input shaft; known as the *pump* or *impellor*, *primary wheel input turbine*

- The other connected to the output shaft, known as the *turbine*, *output turbine*, *secondary wheel* or *runner*

The driving turbine, known as the 'pump', (or *driving torus*) is rotated by the prime mover, which is typically an internal combustion engine or electric motor. The impellor's motion imparts both outwards linear and rotational motion to the fluid.

The hydraulic fluid is directed by the 'pump' whose shape forces the flow in the direction of the 'output turbine' (or *driven torus*). Here, any difference in the angular velocities of 'input stage' and 'output stage' result in a net force on the 'output turbine' causing a torque; thus causing it to rotate in the same direction as the pump.

The motion of the fluid is effectively toroidal - travelling in one direction on paths that can be visualised as being on the surface of a torus:

- If there is a difference between input and output angular velocities the motion has a component which is circular (i.e. round the rings formed by sections of the torus)
- If the input and output stages have identical angular velocities there is no net centripetal force - and the motion of the fluid is circular and co-axial with the axis of rotation (i.e. round the edges of a torus), there is no flow of fluid from one turbine to the other.

Stall speed

An important characteristic of a fluid coupling is its stall speed. The stall speed is defined as the highest speed at which the pump can turn when the output turbine is locked and maximum input power is applied. Under stall conditions all of the engine's power would be dissipated in the fluid coupling as heat, possibly leading to damage.

Step-circuit coupling

A modification to the simple fluid coupling is the step-circuit coupling which was formerly manufactured as the "STC coupling" by the Fluidrive Engineering Company.

The STC coupling contains a reservoir to which some, but not all, of the oil gravitates when the output shaft is stalled. This reduces the "drag" on the input shaft, resulting in reduced fuel consumption when idling and a reduction in the vehicle's tendency to "creep".

When the output shaft begins to rotate, the oil is thrown out of the reservoir by centrifugal force, and returns to the main body of the coupling, so that normal power transmission is restored.

Slip

A fluid coupling cannot develop output torque when the input and output angular velocities are identical. Hence a fluid coupling cannot achieve 100 percent power transmission efficiency. Due to slippage that will occur in any fluid coupling under load, some power will always be lost in fluid friction and turbulence, and dissipated as heat.

The very best efficiency a fluid coupling can achieve is 94%, that is for every 100 revolutions input, there will be 94 revolutions output. Like other fluid dynamical devices, its efficiency tends to increase gradually with increasing scale, as measured by the Reynolds number.

Hydraulic fluid

As a fluid coupling operates kinetically, low viscosity fluids are preferred. Generally speaking, multi-grade motor oils or automatic transmission fluids are used. Increasing density of the fluid increases the amount of torque that can be transmitted at a given input speed.

Hydrodynamic braking

Fluid couplings can also act as hydrodynamic brakes, dissipating rotational energy as heat through frictional forces (both viscous and fluid/container). When a fluid coupling is used for braking it is also known as a *retarder*.

Applications

Industrial

Fluid couplings are used in many industrial application involving rotational power, especially in machine drives that involve high-inertia starts or constant cyclic loading.

Rail transportation

Fluid couplings are found in some Diesel locomotives as part of the power transmission system. Self-Changing Gears made semi-automatic transmissions for British Rail, and Voith manufacture turbo-transmissions for railcars and diesel multiple units which contain various combinations of fluid couplings and torque converters.

Automotive

Fluid couplings were used in a variety of early semi-automatic transmissions and automatic transmissions. Since the late 1940s, the hydrodynamic torque converter has replaced the fluid coupling in automotive applications.

In automotive applications, the pump typically is connected to the flywheel of the engine—in fact, the coupling's enclosure may be part of the flywheel proper, and thus is turned by the engine's crankshaft. The turbine is connected to the input shaft of the transmission. While the transmission is in gear, as engine speed increases torque is transferred from the engine to the input shaft by the motion of the fluid, propelling the vehicle. In this regard, the behavior of the fluid coupling strongly resembles that of a mechanical clutch driving a manual transmission.

Fluid flywheels, as distinct from torque converters, are best known for their use in Daimler cars in conjunction with a Wilson pre-selector gearbox. Daimler used these throughout their range of luxury cars, until switching to automatic gearboxes with the 1958 Majestic. Daimler and Alvis were both also known for their military vehicles and armored cars, some of which also used the combination of pre-selector gearbox and fluid flywheel.

Aviation

The most prominent use of fluid couplings in aeronautical applications was in the Wright turbo-compound reciprocating engine, in which three power recovery turbines extracted approximately 20 percent of the energy or about 500 horsepower (370 kW) from the engine's exhaust gases and then, using three fluid couplings and gearing, converted low-torque high-speed turbine rotation to low-speed, high-torque output to drive the propeller.

Calculations

Generally speaking, the power transmitting capability of a given fluid coupling is strongly related to pump speed, a characteristic that generally works well with applications where the applied load doesn't fluctuate to a great degree. The torque transmitting capacity of any hydrodynamic coupling can be described by the expression $r(N^2)(D^5)$, where r is the mass density of the fluid, N is the impeller speed, and D is the impeller diameter. In the case of automotive applications, where loading can vary to considerable extremes, $r(N^2)(D^5)$ is only an approximation. Stop-and-go driving will tend to operate the coupling in its least efficient range, causing an adverse effect on fuel economy.

Manufacture

Fluid couplings are relatively simple components to produce. For example, the turbines can be aluminum castings or steel stampings, and the housing can also be a casting or made from stamped or forged steel.

Manufacturers of industrial fluid couplings include Voith, Transfluid, TwinDisc, Siemens, PARAG, Fluidomat, and Reuland Electric.

Chapter 12

Wire Rope

Steel wire rope (right hand lay)

Wire rope is a type of rope which consists of several strands of metal wire laid (or 'twisted') into a helix. Initially wrought iron wires were used, but today steel is the main material used for wire ropes.

Historically wire rope evolved from steel chains which had a record of mechanical failure. While flaws in chain links or solid steel bars can lead to catastrophic failure, flaws in the wires making up a steel cable are less critical as the other wires easily take up the load. Friction between the individual wires and strands, as a consequence of their twist, further compensates for any flaws. This method of minimising the effect of flaws may also be seen in Damascus steel, employing multiple folding or laminations.

History and materials

Modern wire rope was invented by the German mining engineer Wilhelm Ducay in the years between 1831 and 1834 for use in mining in the Harz Mountains in Clausthal, Lower Saxony, Germany. It was quickly accepted because it proved superior to ropes made of hemp or to metal chains, such as had been used before.

Wilhelm Albert's first ropes consisted of wires twisted about a hemp rope core, six such strands then being twisted around another hemp rope core in alternating directions for extra stability. Earlier forms of wire rope had been made by covering a bundle of wires with hemp.

In America wire rope was later manufactured by John A. Roebling, forming the basis for his success in suspension bridge building. Roebling introduced a number of innovations in the design, materials and manufacture of wire rope.

Manufacturing a wire rope is similar to making one from natural fibres. The individual wires are first twisted into a strand, then six or so such strands again twisted around a core. This core may consist of steel, but also of natural fibres such as sisal, manila, henequen, jute, or hemp. This is used to cushion off stress forces when bending the rope.

This flexibility is particularly vital in ropes used in machinery such as cranes or elevators as well as ropes used in transportation modes such as cable cars, cable railways, funiculars and aerial lifts. It is not quite so essential in suspension bridges and similar uses.

Wire rope is often sold with vinyl and nylon coatings. This increases weather resistance and overall durability, however it can lead to weak joints if the coating is not removed correctly underneath joints and connections.

Lay of wire rope

Left-hand ordinary lay (LHOL) wire rope (close-up). Right-hand lay strands are laid into a left-hand lay rope.

Right-hand Lang's lay (RHLL) wire rope (close-up). Right-hand lay strands are laid into a right-hand lay rope.

The lay of a wire rope describes the manner in which either the wires in a strand, or the strands in the rope, are laid in a helix.

Left and right hand lay

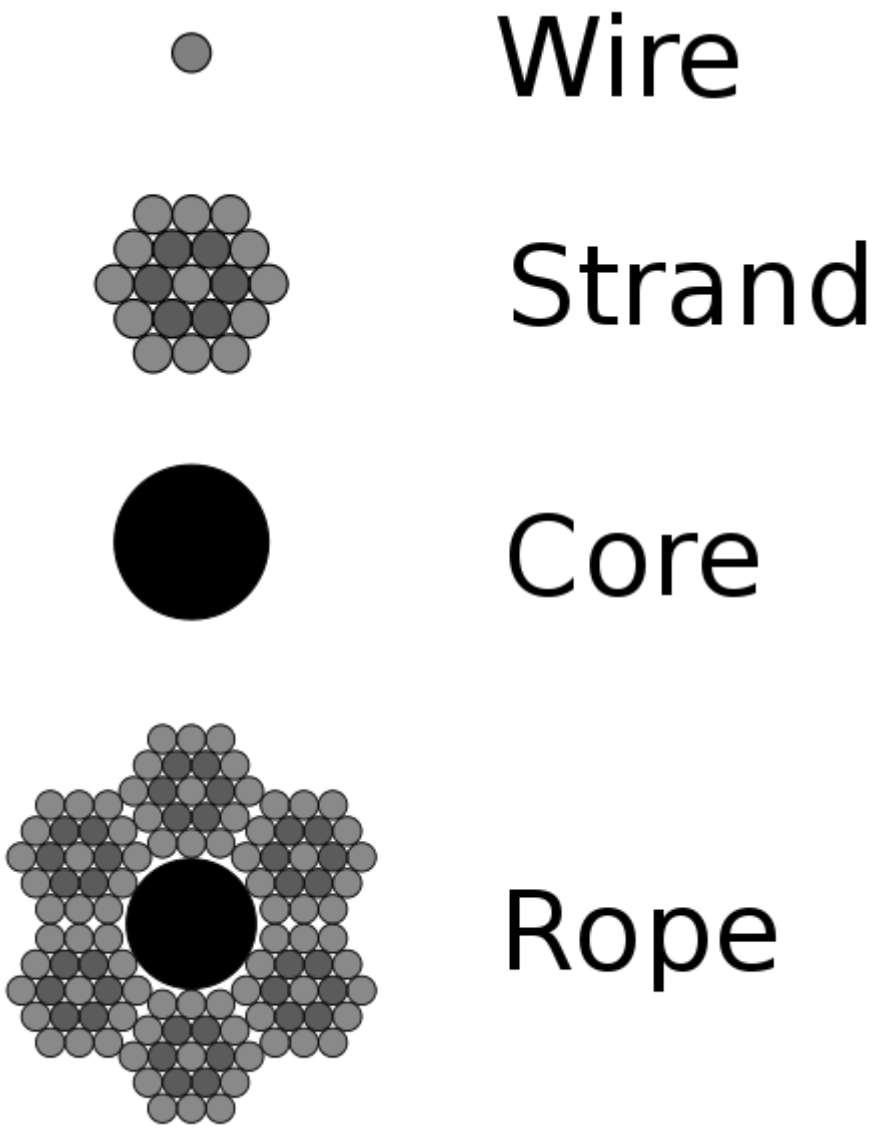
Left hand lay or right hand lay describe the manner in which the strands are laid to form the rope. To determine the lay of strands in the rope, a viewer looks at the rope as it points away from them. If the strands appear to turn in a clockwise direction, or like a right-hand thread, as the strands progress away from the viewer, the rope has a right hand lay. The picture of steel wire rope on this page shows a rope with right hand lay. If the strands appear to turn in an anti-clockwise direction, or like a left-hand thread, as the strands progress away from the viewer, the rope has a left hand lay. (The rope in the left hand lay photo shows one left hand lay rope from left to right and top to bottom, with 5 right hand lay strands, and part of a sixth in the upper left. It is not 5 right hand lay ropes adjacent to each other.)

Ordinary, Lang's and alternate lay

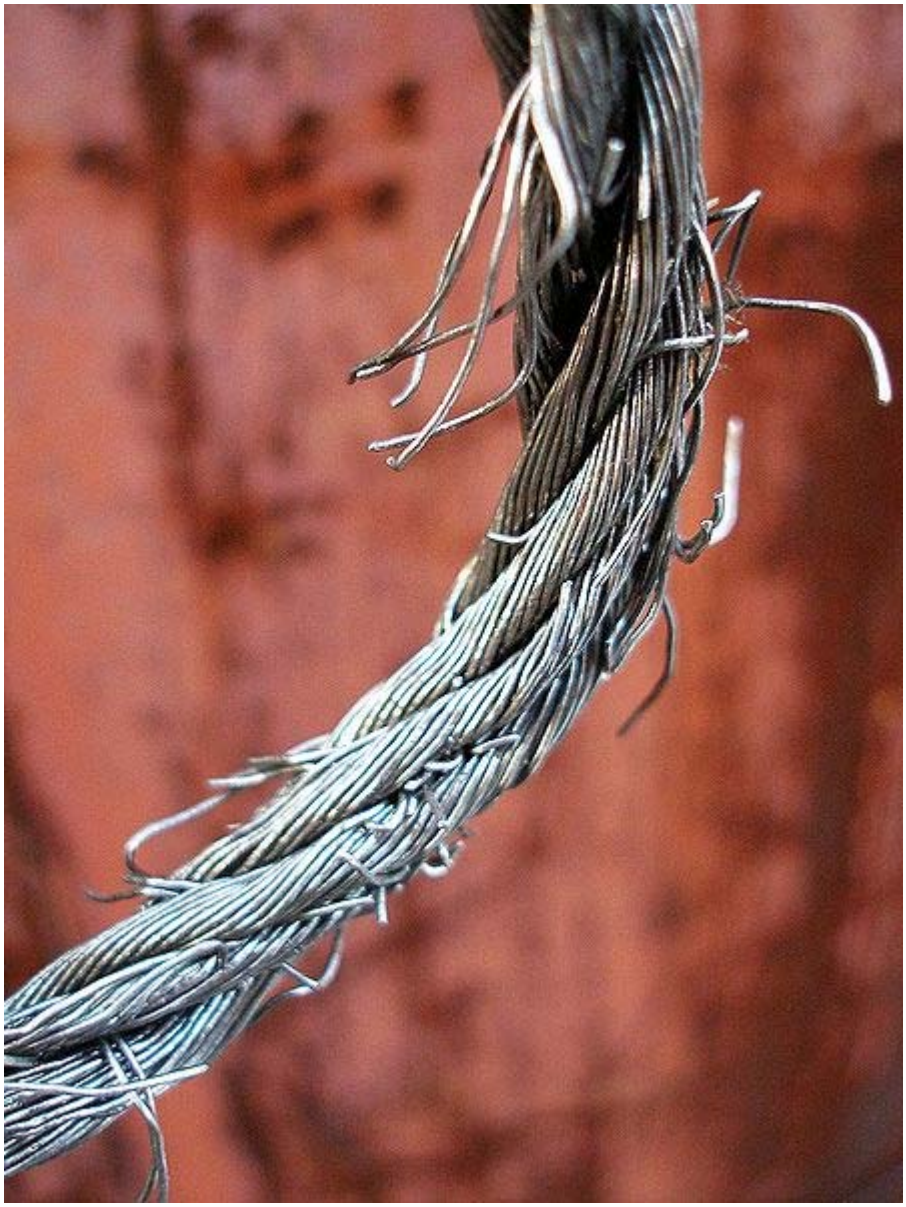
Ordinary and Ducay's lay describe the manner in which the wires are laid to form a strand of the wire rope. To determine which has been used, first identify if left or right hand lay has been used to make the rope. Then identify if a right or left hand lay has been used to twist the wires in each strand. (On ordinary lay, the outer wires approximately follow the alignment of the rope: with Lang's lay they are cross at an angle of about 45°.) Lang's laid rope is able to flex over sheaves more easily (with less damage) but it has the disadvantage of having a high torque tendency (it tends to untwist when tension load is applied) compared with ordinary laid rope. Untwisting can be dangerous with a steel-cored rope: load is shed from the strands and may cause the core to fail as it becomes higher loaded. For this reason, swivel termination units can be dangerous.

Ordinary lay	The lay of wires in each strand is in the opposite direction to the lay of the strands that form the wire.
Lang's lay	The lay of wires in each strand is in the same direction as the lay of the strands that form the wire.
Alternate lay	Strands alternate between Lang's lay and ordinary lay; e.g.: in a 6-strand wire, 3 strands are ordinary lay, and 3 are Lang's lay.
Regular lay	Alternate term for ordinary lay.
Albert's lay	Archaic term for Lang's lay.
Reverse lay	Alternate term for alternate lay.
Spring lay	It refers to a specific construction type of wire rope.

Construction and specification



Wire rope construction



This image of a fraying wire rope shows some individual wires.

The specification of a wire rope type – including the number of wires per strand, the number of strands, and the lay of the rope – is documented using a commonly accepted coding system, consisting of a number of abbreviations.

This is easily demonstrated with a simple example. The rope shown in the figure "Wire rope construction" is designated thus: **6x19 FC RH OL FSWR**

6 Number of strands that make up the rope

19 Number of wires that make up each strand

FC Fibre core

RH Right hand lay
OL Ordinary lay
GSWR Galvanized Steel Wire Rope
FSWR Flexible steel wire rope

Each of the sections of the wire rope designation described above is variable. There are therefore a large number of combinations of wire rope that can be specified in this manner. The following abbreviations are commonly used to specify a wire rope.

Abbr.	Description
FC	Fibre core
FSWR	Flexible steel wire rope
FW	Filler wire
IWR	Independent wire rope
IWRC	Independent wire rope core
J	Jute (fibre)
LH	Left hand lay
LL	Lang's lay
NR	Non-rotating
OL	Ordinary lay
RH	Right hand lay
S	Seale
SF	Seale filler wire
SW	Seale Warrington
SWL	Safe working load
TS	Triangular strand
W	Warrington
WF	Warriflex
WLL	Working load limit
WS	Warrington Seale

Warrington differs from the other types (Filler Wire and Seale construction) in that the outside layer of wires in each strand of the wire rope is composed of wires alternately large and small. The outside wires of both the Filler Wire and Seale construction ropes are uniform in size. The fundamental difference between these types is that the layer of wires underneath the outside layer in the Seale type is made up of wires all of the same size. The wires under the outside layer of the Filler Wire rope are made up of a combination of main wires, each of the same size, and smaller filler wires, each of the same size, nested between the main wires. The outside layer of wires, therefore, is supported partly by the main inside wires and partly by the filler wires.

Some ropes have shaped or formed (triangular) wires to improve the wear and bearing properties of the outer layers (rather than circular drawn wire).

By having different lay directions of the strands and wire (left and right - also known as S and Z), it is possible to balance the torque value - resulting in a rope that does not tend to untwist when load is applied. This is called torque balanced or non-rotating rope.

Terminations

Right-hand ordinary lay (RHOL) wire rope terminated in a loop with a thimble and ferrule.

The end of a wire rope tends to fray readily, and cannot be easily connected to plant and equipment. There are different ways of securing the ends of wire ropes to prevent fraying. The most common and useful type of end fitting for a wire rope is to turn the end back to form a loop. The loose end is then fixed back on the wire rope. Termination efficiencies vary from about 70% for a Flemish eye alone; to nearly 90% for a Flemish eye and splice; to 100% for potted ends and swagings.

Thimbles

When the wire rope is terminated with a loop, there is a risk that it will bend too tightly, especially when the loop is connected to a device that spreads the load over a relatively small area. A thimble can be installed inside the loop to preserve the natural shape of the loop, and protect the cable from pinching and abrading on the inside of the loop. The use of thimbles in loops is industry best practice. The thimble prevents the load from coming into direct contact with the wires.

Wire rope clamps/clips

A wire rope clamp, also called a clip, is used to fix the loose end of the loop back to the wire rope. It usually consists of a u-shaped bolt, a forged saddle and two nuts. The two layers of wire rope are placed in the u-bolt. The saddle is then fitted over the ropes on to the bolt (the saddle includes two holes to fit to the u-bolt). The nuts secure the arrangement in place. Three or more clamps are usually used to terminate a wire rope. As many as eight may be needed for a 2 in (50.8 mm) diameter rope. There is an old adage which has over time became the rule; when installing clamps to secure the loop at the end

of your wire rope make sure you do not "saddle a dead horse." The saddle portion of the clamp assembly is placed and tightened on the opposite side of the terminal end of the cable (the load bearing or live end). According to the US Navy Manual S9086-UU-STM-010, Chapter 613R3, Wire and Fiber Rope and Rigging, "This is to protect the live or stress-bearing end of the rope against crushing and abuse. The flat bearing seat and extended prongs of the body (saddle) are designed to protect the rope and are always placed against the live end." The US Navy and most regulatory bodies do not recommend the use of such clips as permanent terminations.

Swaged terminations

Swaging is a method of wire rope termination that refers to the installation technique. The purpose of swaging wire rope fittings is to connect two wire rope ends together, or to otherwise terminate one end of wire rope to something else. A mechanical or hydraulic swager is used to compress and deform the fitting, creating a permanent connection. There are many types of swaged fittings. Threaded Studs, Ferrules, Sockets, and Sleeves a few examples. Swaging ropes with fibre cores is not recommended.

Wedge Sockets

A wedge socket termination is useful when the fitting needs to be replaced frequently. For example, if the end of a wire rope is in a high-wear region, the rope may be periodically trimmed, requiring the termination hardware to be removed and reapplied. An example of this is on the ends of the drag ropes on a dragline. The end loop of the wire rope enters a tapered opening in the socket, wrapped around a separate component called the wedge. The arrangement is knocked in place, and load gradually eased onto the rope. As the load increases on the wire rope, the wedge become more secure, gripping the rope tighter.

Potted ends or Poured sockets

Poured sockets are used to make a high strength, permanent termination; they are created by inserting the wire rope into the narrow end of a conical cavity which is oriented in-line with the intended direction of strain. The individual wires are splayed out inside the cone, and the cone is then filled with molten zinc, or now more commonly, an epoxy resin compound.

Eye splice or Flemish eye

The ends of individual strands of this eye splice used aboard a cargo ship are served with natural fiber cord after the splicing is complete. This helps protect seaman's hands when handling.

An eye splice may be used to terminate the loose end of a wire rope when forming a loop. The strands of the end of a wire rope are unwound a certain distance, and plaited back into the wire rope, forming the loop, or an eye, called an eye splice. When this type of rope splice is used specifically on wire rope, it is called a "Molly Hogan", and, by some, a "Dutch" eye instead of a "Flemish" eye.

Codes and standards

Australia

The following Australian Standards apply to wire rope:

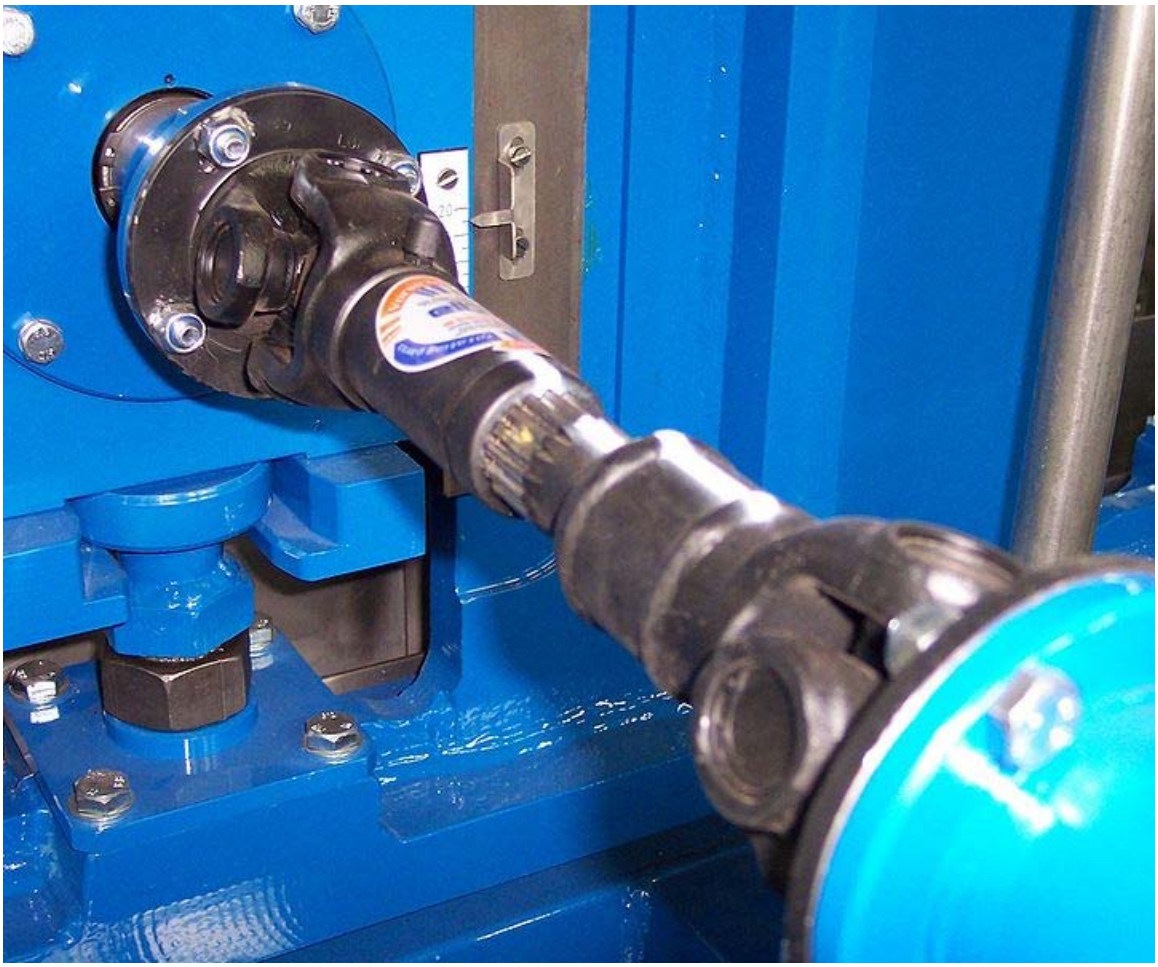
- AS 1138-1992 Thimbles for wire rope
- AS 1394-2001 Round steel wire for ropes
- AS 1666.1-1995 Wire-rope slings - Product specification
- AS 1666.2-1995 Wire-rope slings - Care and use
- AS 2076-1996 Wire-rope grips for non-lifting applications
- AS 2759-2004 Steel wire rope - Use, operation and maintenance
- AS 3569-1989 Steel wire ropes
- AS/NZS 4812-2003 Non-destructive examination and discard criteria for wire ropes in mine winding systems

The following EN Standards apply to wire rope:

The other Parts of EN 12385 are: Part 1: General requirements Part 2: Definitions, designation and classification Part 3: Information for use and maintenance Part 4: Stranded ropes for general lifting applications Part 5: Stranded ropes for lifts Part 6: Stranded ropes for mine shafts Part 7: Locked coil ropes for mine shafts Part 8: Stranded hauling and carrying-hauling ropes for cableway installations designed to carry persons Part 9: Locked coil carrying ropes for cableway installations designed to carry persons Part 10: Spiral ropes for general structural applications

Chapter 13

Drive Shaft



Drive shaft with universal joints at each end and a spline in the center

A **drive shaft**, **driveshaft**, **driving shaft**, **propeller shaft**, or **Cardan shaft** is a mechanical component for transmitting torque and rotation, usually used to connect other components of a drive train that cannot be connected directly because of distance or the need to allow for relative movement between them.

Drive shafts are carriers of torque: they are subject to torsion and shear stress, equivalent to the difference between the input torque and the load. They must therefore be strong enough to bear the stress, whilst avoiding too much additional weight as that would in turn increase their inertia.

Drive shafts frequently incorporate one or more universal joints or jaw couplings, and sometimes a splined joint or prismatic joint to allow for variations in the alignment and distance between the driving and driven components.

History

The term **drive shaft** first appeared during the mid 19th century. In Storer's 1861 patent reissue for a planing and matching machine, the term is used to refer to the belt-driven shaft by which the machine is driven. The term is not used in his original patent. Another early use of the term occurs in the 1861 patent reissue for the Watkins and Bryson horse-drawn mowing machine. Here, the term refers to the shaft transmitting power from the machine's wheels to the gear train that works the cutting mechanism.

In the 1890s, the term began to be used in a manner closer to the modern sense. In 1891, for example, Battles referred to the shaft between the transmission and driving trucks of his Climax locomotive as the drive shaft, and Stillman referred to the shaft linking the crankshaft to the rear axle of his shaft-driven bicycle as a drive shaft. In 1899, Bukey used the term to describe the shaft transmitting power from the wheel to the driven machinery by a universal joint in his Horse-Power. In the same year, Clark described his Marine Velocipede using the term to refer to the gear-driven shaft transmitting power through a universal joint to the propeller shaft. Crompton used the term to refer to the shaft between the transmission of his steam-powered Motor Vehicle of 1903 and the driven axle.

Automotive drive shafts

Vehicles

An automobile may use a longitudinal shaft to deliver power from an engine/transmission to the other end of the vehicle before it goes to the wheels. A pair of short drive shafts is commonly used to send power from a central differential, transmission, or transaxle to the wheels.

A truck double propeller shaft

Front-engine, rear-wheel drive

In front-engined, rear-drive vehicles, a longer drive shaft is also required to send power the length of the vehicle. Two forms dominate: The torque tube with a single universal joint and the more common Hotchkiss drive with two or more joints. This system became known as *Système Panhard* after the automobile company Panhard et Levassor patented it.

Most of these vehicles have a clutch and gearbox (or transmission) mounted directly on the engine with a drive shaft leading to a final drive in the rear axle. When the vehicle is stationary, the drive shaft does not rotate. A few, mostly sports, cars seeking improved weight balance between front and rear, and most commonly Alfa Romeos or Porsche 924s, have instead used a rear-mounted transaxle. This places the clutch and transmission at the *rear* of the car and the drive shaft between them and the engine. In this case the drive shaft rotates continuously as long as the engine does, even when the car is stationary and out of gear.

Early automobiles often used chain drive or belt drive mechanisms rather than a drive shaft. Some used electrical generators and motors to transmit power to the wheels.

Front-wheel drive

In British English, the term "drive shaft" is restricted to a transverse shaft that transmits power to the wheels, especially the front wheels. A drive shaft connecting the gearbox to

a rear differential is called a **propeller shaft**, or **prop-shaft**. A prop-shaft assembly consists of a propeller shaft, a slip joint and one or more universal joints. Where the engine and axles are separated from each other, as on four-wheel drive and rear-wheel drive vehicles, it is the propeller shaft that serves to transmit the drive force generated by the engine to the axles.

A drive shaft connecting a rear differential to a rear wheel may be called a **half shaft**. The name derives from the fact that two such shafts are required to form one rear axle.

Several different types of drive shaft are used in the automotive industry:

- One-piece drive shaft
- Two-piece drive shaft
- Slip-in-tube drive shaft

The slip-in-tube drive shaft is a new type that also helps in crash energy management. It can be compressed in the event of a crash, so is also known as a collapsible drive shaft.

Four wheel and all-wheel drive

These evolved from the front-engine rear-wheel drive layout. A new form of transmission called the transfer case was placed between transmission and final drives in both axles. This split the drive to the two axles and may also have included reduction gears, a dog clutch or differential. At least two drive shafts were used, one from the transfer case to each axle. In some larger vehicles, the transfer box was centrally mounted and was itself driven by a short drive shaft. In vehicles the size of a Land Rover, the drive shaft to the front axle is noticeably shorter and more steeply articulated than the rear shaft, making it a more difficult engineering problem to build a reliable drive shaft, and which may involve a more sophisticated form of universal joint.

Modern light cars with all-wheel drive (notably Audi or the Fiat Panda) may use a system that more closely resembles a front-wheel drive layout. The transmission and final drive for the front axle are combined into one housing alongside the engine, and a *single* drive shaft runs the length of the car to the rear axle. This is a favoured design where the torque is biased to the front wheels to give car-like handling, or where the maker wishes to produce both four-wheel drive and front-wheel drive cars with many shared components.

Drive shaft for Research and Development (R&D)

The automotive industry also uses drive shafts at testing plants. At an engine test stand a drive shaft is used to transfer a certain speed / torque from the Internal combustion engine to a dynamometer. A "shaft guard" is used at a shaft connection to protect against contact with the drive shaft and for detection of a shaft failure. At a transmission test stand a drive shaft connects the prime mover with the transmission.

Motorcycle drive shafts

A 1913 FN (Fabrique Nationale), Belgium, 4cylinders and shaft drive

A 1923 BMW R32, with a shaft-drive, boxer twin engine

Drive shafts have been used on motorcycles almost as long as there have been motorcycles. As an alternative to chain and belt drives, drive shafts offer relatively maintenance-free operation and long life. A disadvantage of shaft drive on a motorcycle is that gearing or a Hobson's joint or similar is needed to turn the power 90° from the shaft to the rear wheel, losing some power in the process. On the other hand, it is easier to protect the shaft linkages and drive gears from dust, sand and mud.

The best known motorcycle manufacturer to use shaft drive for a long time—since 1923—is BMW. Among contemporary manufacturers, Moto Guzzi is also well-known for its shaft drive motorcycles. The British company, Triumph and all four Japanese brands, Honda, Suzuki, Kawasaki and Yamaha, have produced shaft drive motorcycles. All geared models of the Vespa scooter produced to date have been shaft-driven. The automatic models, however, use a belt.

Motorcycle engines positioned such that the crankshaft is longitudinal and parallel to the frame are often used for shaft driven motorcycles. This requires only one 90° turn in power transmission, rather than two. Bikes from Moto Guzzi and BMW, plus the Triumph Rocket III and Honda ST series all use this engine layout.

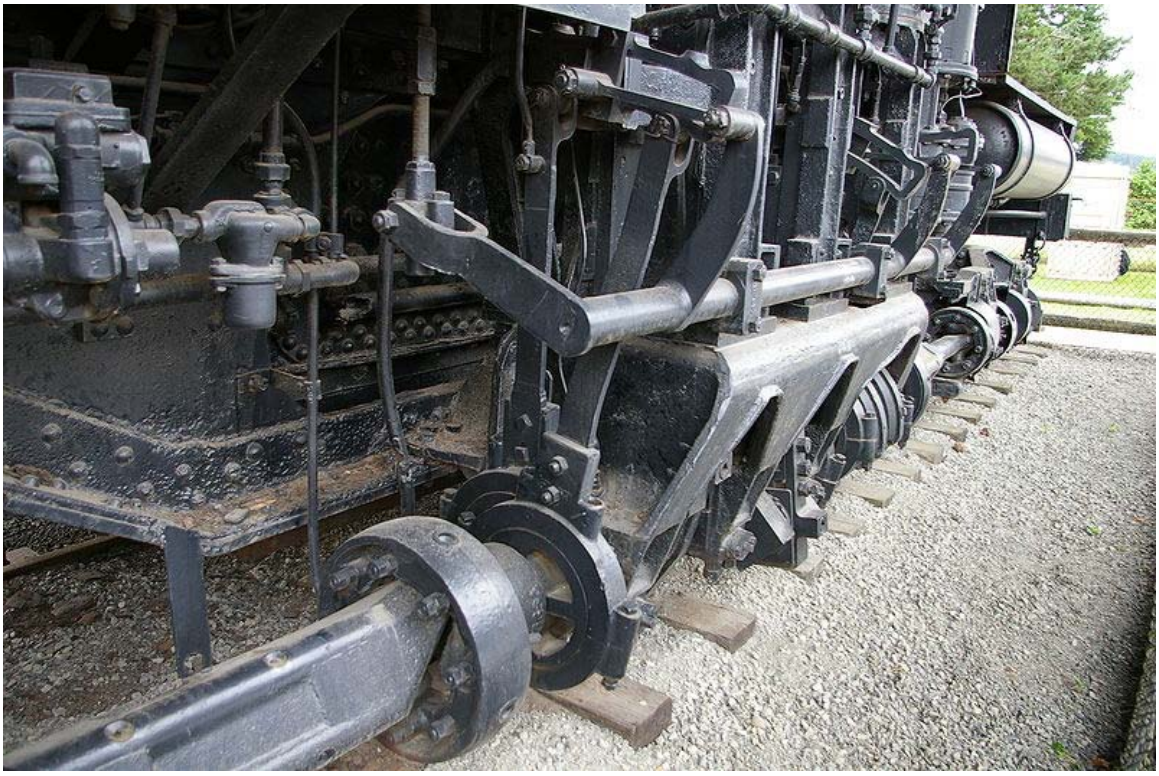
Motorcycles with shaft drive are subject to shaft effect where the chassis climbs when power is applied. This is counteracted with systems such as BMW's Paralever, Moto Guzzi's CARC and Kawasaki's Tetra Lever.

Marine drive shafts

On a power-driven ship, the drive shaft, or propeller shaft, usually connects the transmission inside the vessel directly to the propeller, passing through a stuffing box or other seal at the point it exits the hull. There is also a thrust block, a bearing to resist the axial force of the propeller. As the rotating propeller pushes the vessel forward, any length of drive shaft between propeller and thrust block is subject to compression, and when going astern to tension. Except for the very smallest of boats, this force isn't taken on the gearbox or engine directly.

Cardan shafts are also often used in marine applications between the transmission and either a propeller gearbox or waterjet.

Locomotive drive shafts



The rear drive shaft, crankshaft and front drive shaft of a Shay locomotive.

The Shay, Climax and Heisler locomotives, all introduced in the late 19th century, used quill drives to couple power from a centrally mounted multi-cylinder engine to each of the trucks supporting the engine. On each of these geared steam locomotives, one end of each drive shaft was coupled to the driven truck through a universal joint while the other end was powered by the crankshaft, transmission or another truck through a second universal joint. A quill drive also has the ability to slide lengthways, effectively varying its length. This is required to allow the bogies to rotate when passing a curve.

Cardan shafts are used in some diesel locomotives (mainly diesel-hydraulics, such as British Rail Class 52) and some electric locomotives (e.g. British Rail Class 91). They are also widely used in diesel multiple units.

Drive shafts in bicycles

A shaft-driven bicycle.

The drive shaft has served as an alternative to a chain-drive in bicycles for the past century, although never becoming very popular. A shaft-driven bicycle is described as an "Acatane", from one of their early makers. When used on a bicycle, a drive shaft has several advantages and disadvantages:

Advantages

- Drive system is less likely to become jammed, a common problem with chain-driven bicycles
- The rider cannot become dirtied from chain grease or injured by the chain from "Chain bite", which occurs when clothing or even a body part catches between the chain and a sprocket
- Lower maintenance than a chain system when the drive shaft is enclosed in a tube
- More consistent performance. Dynamic Bicycles claims that a drive shaft bicycle can deliver 94% efficiency, whereas a chain-driven bike can deliver anywhere from 75-97% efficiency based on condition
- Greater clearance: with the absence of a derailleur or other low-hanging machinery, the bicycle has nearly twice the ground clearance

Disadvantages

- A drive shaft system weighs more than a chain system, usually 1-2 pounds heavier
- At optimum upkeep, a chain delivers greater efficiency
- Many of the advantages claimed by drive shaft's proponents can be achieved on a chain-driven bicycle, such as covering the chain and gears with a metal or plastic cover
- Use of lightweight derailleur gears with a high number of ratios is impossible, although hub gears can be used
- Wheel removal can be complicated in some designs (as it is for some chain-driven bicycles with hub gears).