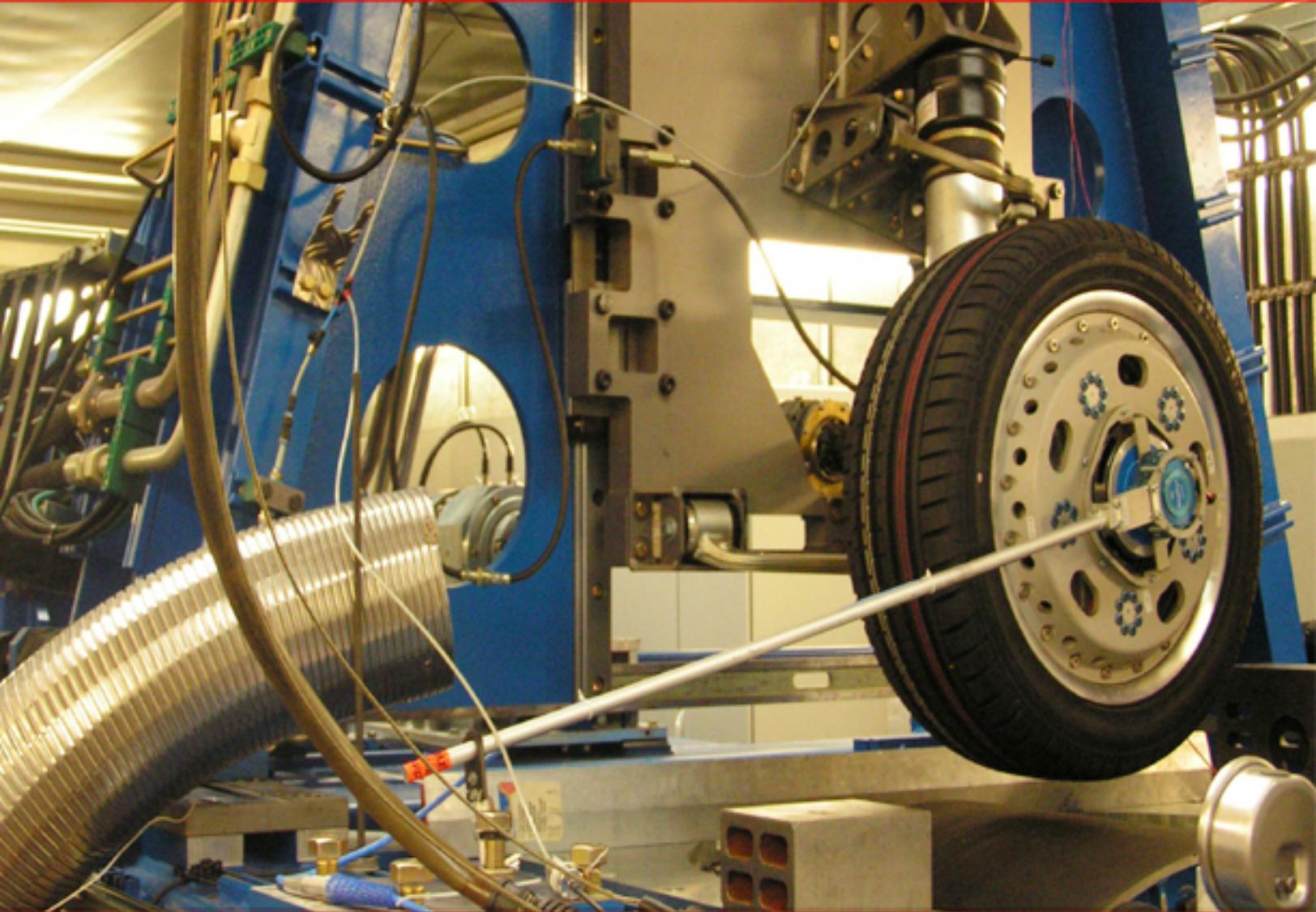


Automotive Engineering



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Introduction

Modern **automotive engineering** is a branch of vehicle engineering, incorporating elements of mechanical, electrical, electronic, software and safety engineering as applied to the design, manufacture and operation of motorcycles, automobiles, buses and trucks and their respective engineering subsystems.

Product Engineering

Some of the engineering attributes/disciplines that are of importance to the automotive engineer:

Safety Engineering: Safety Engineering is the assessment of various crash scenarios and their impact on the vehicle occupants. These are tested against very stringent governmental regulations. Some of these requirements include: Seat belt and air bag functionality. Front and side crash worthiness. Resistance to rollover. Assessments are done with various methods and tools: Computer crash simulation, crash test dummies, partial system sled and full vehicle crashes.

Fuel Economy/Emissions: Fuel economy is the measured fuel efficiency of the vehicle in miles per gallon or litres per 100 kilometers. Emissions testing the measurement of the vehicles emissions: hydrocarbons, nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂), and evaporative emissions.

Vehicle Dynamics: Vehicle dynamics is the vehicle's response of the following attributes: ride, handling, steering, braking, and traction. Design of the chassis systems of suspension, steering, braking, structure (frame), wheels and tires, and traction control are highly leveraged by the Vehicle Dynamics engineer to deliver the Vehicle Dynamics qualities desired.

NVH Engineering (Noise, Vibration, and Harshness): NVH is the customer's impression both tactile (feel) and audible (hear) feedback from the vehicle. While sound can be interpreted as a rattle, squeal, or hoot, a tactile response can be seat vibration, or a buzz in the steering wheel. This feedback is generated by components

either rubbing, vibrating or rotating. NVH response can be classified in various ways: powertrain NVH, road noise, wind noise, component noise, and squeak and rattle. Note, there are both good and bad NVH qualities. The NVH engineer works to either eliminate bad NVH, or change the “bad NVH” to good (i.e., exhaust tones).

Performance: Performance is a measurable and testable value of a vehicles ability to perform in various conditions. Performance can be considered in a wide variety of tasks, but it's generally associated with how quickly a car can accelerate (i.e. 0-60 mph, 1/4 mile, trap speed, top speed, etc), how short and quickly a car can come to a complete stop from a set distance (i.e. 70-0 mph), how many g-forces a car can generate without losing grip, figure 8, recorded trap lap times, cornering speed, brake fade, etc. Performance can also reflect the amount of control in inclement weather (snow, ice, rain).

Shift Quality: Shift Quality is the driver’s perception of the vehicle to an automatic transmission banana event. This is influenced by the powertrain (engine, transmission), and the vehicle (driveline, suspension, etc). Shift feel is both a tactile (feel) and audible (hear) response of the vehicle. Shift Quality is experienced as various events: Transmission shifts are felt as an upshift at acceleration (1-2), or a downshift maneuver in passing (4-2). Shift engagements of the vehicle are also evaluated, as in Park to Reverse, etc.

Durability / Corrosion engineering: Durability and Corrosion engineering is the evaluation testing of a vehicle for its useful life. This includes mileage accumulation, severe driving conditions, and corrosive salt baths.

Package / Ergonomics Engineering: Package Engineering is a discipline that designs/analyzes the occupant accommodations (seat roominess), ingress/egress to the vehicle, and the driver’s field of vision (gauges and windows). The Package Engineer is also responsible for other areas of the vehicle like the engine compartment, and the component to component placement. Ergonomics is the discipline that assesses the occupant's access to the steering wheel, pedals, and other driver/passenger controls.

Climate Control: Climate Control is the customer’s impression of the cabin environment and level of comfort related to the temperature and humidity. From the windshield defrosting, to the heating and cooling capacity, all vehicle seating positions are evaluated to a certain level of comfort.

Drivability: Drivability is the vehicle’s response to general driving conditions. Cold starts and stalls, rpm dips, idle response, launch hesitations and stumbles, and performance levels.

Cost: The cost of a vehicle program is typically split into the effect on the variable cost of the vehicle, and the up-front tooling and fixed costs associated with

developing the vehicle. There are also costs associated with warranty reductions, and marketing.

Program timing: To some extent programs are timed with respect to the market, and also to the production schedules of the assembly plants. Any new part in the design must support the development and manufacturing schedule of the model.

Assembly Feasibility: It is easy to design a module that is hard to assemble, either resulting in damaged units, or poor tolerances. The skilled product development engineer works with the assembly/manufacturing engineers so that the resulting design is easy and cheap to make and assemble, as well as delivering appropriate functionality and appearance.

Development Engineer

A Development Engineer is a job function within Automotive Engineering, in which the development engineer has the responsibility for coordinating delivery of the engineering attributes of a complete automobile (bus, car, truck, van, SUV, etc.) as dictated by the automobile manufacturer, governmental regulations, and the customer who buys the product.

Much like the Systems Engineer, the Development Engineer is concerned with the interactions of all systems in the complete automobile. While there are multiple components and systems in an automobile that have to function as designed, they must also work in harmony with the complete automobile. As an example, the brake system's main function is to provide braking functionality to the automobile. Along with this, it must also provide an acceptable level of: pedal feel (spongy, stiff), brake system “noise” (squeal, shudder, etc), and interaction with the ABS (anti-lock braking system)

Another aspect of the development engineer's job is a trade-off process required to deliver all the automobile attributes at a certain acceptable level. An example of this is the trade-off between engine performance and fuel economy. While some customers are looking for maximum power from their engine, the automobile is still required to deliver an acceptable level of fuel economy. From the engine's perspective, these are opposing requirements. Engine performance is looking for maximum displacement (bigger, more power), while fuel economy is looking for a smaller displacement engine (ex: 1.4 L vs. 5.4 L). The engine size, though is not the only contributing factor to fuel economy and automobile performance. Other attributes include: automobile weight, aerodynamic drag, transmission gearing, emission control devices, and tires.

The Development Engineer is also responsible for organising automobile level testing, validation, and certification. Components and systems are designed and tested individually by the Product Engineer. The final evaluation though, has to be conducted at the automobile level to evaluate system to system interactions. As an

example, the audio system (radio) needs to be evaluated at the automobile level. Interaction with other electronic components can cause interference. Heat dissipation of the system and ergonomic placement of the controls need to be evaluated. Sound quality in all seating positions needs to be provided at acceptable levels.

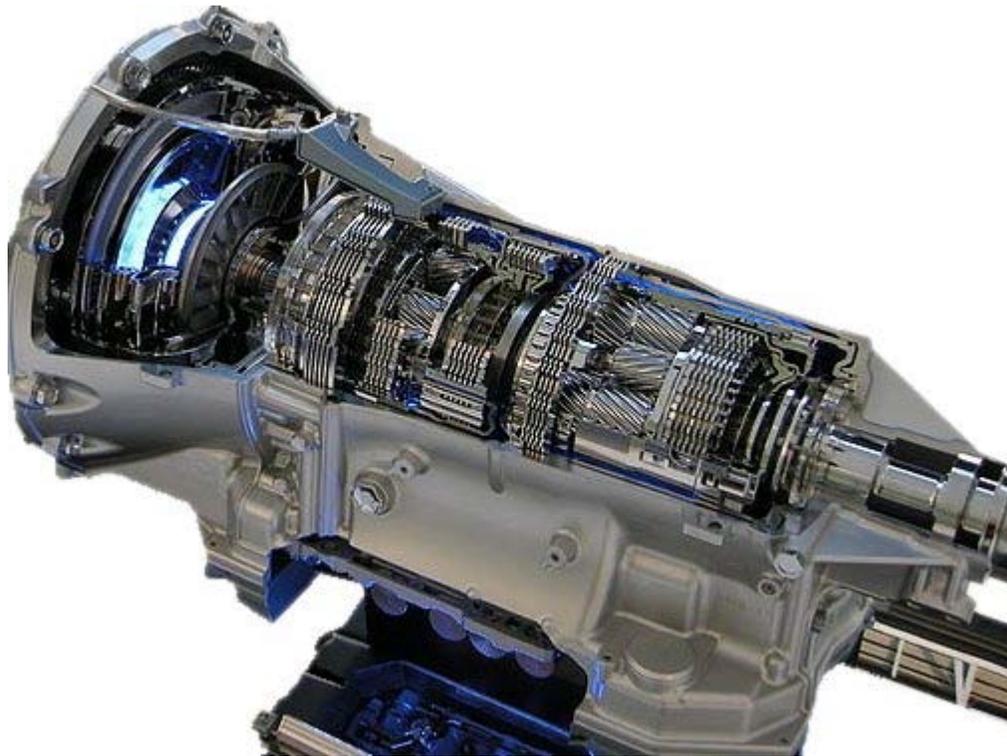
Other automotive engineering roles

There are also other automotive engineers:

- The aerodynamics engineers will often give guidance to the styling studio so that the shapes they design are aerodynamic, as well as attractive.
- Body engineers will also let the studio know if it is feasible to make the panels for their designs.

Chapter 1

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 transmissions 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, 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 Dynaflo 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 2

Suspension (Vehicle) & Automotive Suspension Design

Suspension (Vehicle)



The front suspension components of a Ford Model T.



The rear suspension on a truck: a leaf spring.



Part of car front suspension and steering mechanism: tie rod, steering arm, king pin axis (using ball joints).

Suspension is the term given to the system of springs, shock absorbers and linkages that connects a vehicle to its wheels. Suspension systems serve a dual purpose — contributing to the car's roadholding/handling and braking for good active safety and driving pleasure, and keeping vehicle occupants comfortable and reasonably well isolated from road noise, bumps, and vibrations, etc. These goals are generally at odds, so the tuning of suspensions involves finding the right compromise. It is important for the suspension to keep the road wheel in contact with the road surface as much as possible, because all the forces acting on the vehicle do so through the contact patches of the tires. The suspension also protects the vehicle itself and any

cargo or luggage from damage and wear. The design of front and rear suspension of a car may be different.

History

Leaf springs have been around since the early Egyptians.

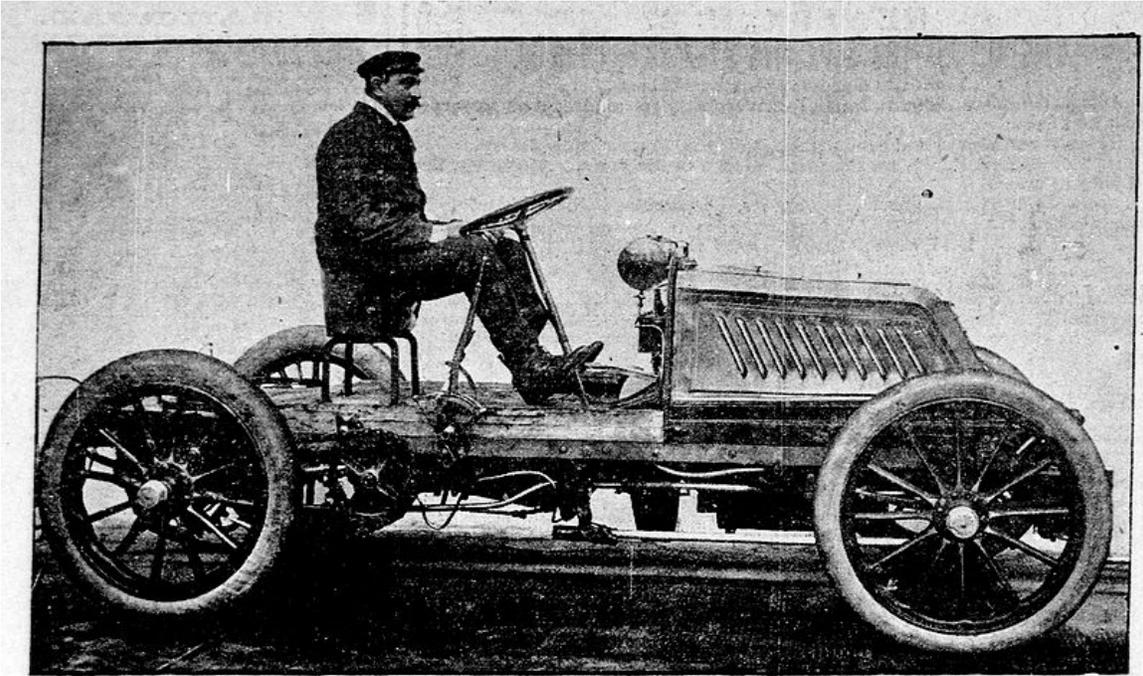
Ancient military engineers used leaf springs in the form of bows to power their siege engines, with little success at first. The use of leaf springs in catapults was later refined and made to work years later. Springs were not only made of metal, a sturdy tree branch could be used as a spring, such as with a bow.

Horse drawn vehicles

By the early 19th century, most British horse carriages were equipped with springs; wooden springs in the case of light one-horse vehicles to avoid taxation, and steel springs in larger vehicles. These were made of low-carbon steel and usually took the form of multiple layer leaf springs.

The British steel springs were not well suited for use on America's rough roads of the time, and could even cause coaches to collapse if cornered too fast. In the 1820s, the Abbot Downing Company of Concord, New Hampshire developed a system whereby the bodies of stagecoaches were supported on leather straps called "thoroughbraces", which gave a swinging motion instead of the jolting up and down of a spring suspension (the stagecoach itself was sometimes called a "thoroughbrace").

Automobiles



FOURNIER ON THE "MORS" MACHINE WITH WHICH HE WON THE PAR IS-BORDEAUX AND PARIS-BERLIN RACES AND BEAT THE VANDERBILT RECORD FOR ONE KILOMETRE.

Henri Fournier on his uniquely dampened and racewinning 'Mors Machine', photo taken 1902

Automobiles were initially developed as self-propelled versions of horse drawn vehicles. However, horse drawn vehicles had been designed for relatively slow speeds and their suspension was not well suited to the higher speeds permitted by the internal combustion engine.

In 1901 Mors of Germany first fitted an automobile with shock absorbers. With the advantage of having a dampened suspension system in his 'Mors Machine', Henri Fournier was able to win the prestigegous Paris — Berlin race on June 20, 1901. Fourniers superior time was 11 hrs 46 min 10 sec, while the best competitor was Léonce Girardot in a Panhard at the time 12 hrs 15 min 40 sec.

In 1920, Leyland used torsion bars in a suspension system. In 1922, independent front suspension was pioneered on the Lancia Lambda and became more common in mass market cars from 1932.

Important properties



Citroën BX Hydro-pneumatic suspension - maximum to minimum demonstration

Spring rate

The spring rate (or suspension rate) is a component in setting the vehicle's ride height or its location in the suspension stroke. Vehicles which carry heavy loads will often have heavier springs to compensate for the additional weight that would otherwise collapse a vehicle to the bottom of its travel (stroke). Heavier springs are also used in performance applications where the loading conditions experienced are more extreme.

Springs that are too hard or too soft cause the suspension to become ineffective because they fail to properly isolate the vehicle from the road. Vehicles that commonly experience suspension loads heavier than normal have heavy or hard springs with a spring rate close to the upper limit for that vehicle's weight. This allows the vehicle to perform properly under a heavy load when control is limited by the inertia of the load. Riding in an empty truck used for carrying loads can be uncomfortable for passengers because of its high spring rate relative to the weight of the vehicle. A race car would also be described as having heavy springs and would also be uncomfortably bumpy. However, even though we say they both have heavy springs, the actual spring rates for a 2,000 lb (910 kg) race car and a 10,000 lb (4,500

kg) truck are very different. A luxury car, taxi, or passenger bus would be described as having soft springs. Vehicles with worn out or damaged springs ride lower to the ground which reduces the overall amount of compression available to the suspension and increases the amount of body lean. Performance vehicles can sometimes have spring rate requirements other than vehicle weight and load.

Mathematics of the spring rate

Spring rate is a ratio used to measure how resistant a spring is to being compressed or expanded during the spring's deflection. The magnitude of the spring force increases as deflection increases according to Hooke's Law. Briefly, this can be stated as

$$F = -kx$$

where

F is the force the spring exerts

k is the spring rate of the spring.

x is the displacement from equilibrium length i.e. the length at which the spring is neither compressed or stretched.

Spring rate is confined to a narrow interval by the weight of the vehicle, load the vehicle will carry, and to a lesser extent by suspension geometry and performance desires.

Spring rates typically have units of N/mm (or lbf/in). An example of a linear spring rate is 500 lbf/in. For every inch the spring is compressed, it exerts 500 lbf. A non-linear spring rate is one for which the relation between the spring's compression and the force exerted cannot be fitted adequately to a linear model. For example, the first inch exerts 500 lbf force, the second inch exerts an additional 550 lbf (for a total of 1050 lbf), the third inch exerts another 600 lbf (for a total of 1650 lbf). In contrast a 500 lbf/in linear spring compressed to 3 inches will only exert 1500 lbf.

The spring rate of a coil spring may be calculated by a simple algebraic equation or it may be measured in a spring testing machine. The spring constant k can be calculated as follows:

$$k = \frac{d^4 G}{8ND^3}$$

where d is the wire diameter, G is the spring's shear modulus (e.g., about 12,000,000 lbf/in² or 80 GPa for steel), and N is the number of wraps and D is the diameter of the coil.

Wheel rate

Wheel rate is the effective spring rate when measured at the wheel. This is as opposed to simply measuring the spring rate alone.

Wheel rate is usually equal to or considerably less than the spring rate. Commonly, springs are mounted on control arms, swing arms or some other pivoting suspension member. Consider the example above where the spring rate was calculated to be 500 lbs/inch, if you were to move the wheel 1 in (2.5 cm) (without moving the car), the spring more than likely compresses a smaller amount. Lets assume the spring moved 0.75 in (19 mm), the lever arm ratio would be 0.75:1. The wheel rate is calculated by taking the square of the ratio (0.5625) times the spring rate. Squaring the ratio is because the ratio has two effects on the wheel rate. The ratio applies to both the force and distance traveled.

Wheel rate on independent suspension is fairly straight-forward. However, special consideration must be taken with some non-independent suspension designs. Take the case of the straight axle. When viewed from the front or rear, the wheel rate can be measured by the means above. Yet because the wheels are not independent, when viewed from the side under acceleration or braking the pivot point is at infinity (because both wheels have moved) and the spring is directly inline with the wheel contact patch. The result is often that the effective wheel rate under cornering is different from what it is under acceleration and braking. This variation in wheel rate may be minimized by locating the spring as close to the wheel as possible.

Roll couple percentage

Roll couple percentage is the effective wheel rate, in roll, of each axle of the vehicle as a ratio of the vehicle's total roll rate. Roll couple percentage is critical in accurately balancing the handling of a vehicle. It is commonly adjusted through the use of anti-roll bars, but can also be changed through the use of different springs.

A vehicle with a roll couple percentage of 70% will transfer 70% of its sprung weight at the front of the vehicle during cornering. This is also commonly known as "Total Lateral Load Transfer Distribution" or "TLLTD".

Weight transfer

Weight transfer during cornering, acceleration or braking is usually calculated per individual wheel and compared with the static weights for the same wheels.

The total amount of weight transfer is only affected by four factors: the distance between wheel centers (wheelbase in the case of braking, or track width in the case of cornering) the height of the center of gravity, the mass of the vehicle, and the amount of acceleration experienced.

The speed at which weight transfer occurs as well as through which components it transfers is complex and is determined by many factors including but not limited to roll center height, spring and damper rates, anti-roll bar stiffness and the kinematic design of the suspension links.

Unsprung weight transfer

Unsprung weight transfer is calculated based on the weight of the vehicle's components that are not supported by the springs. This includes tires, wheels, brakes, spindles, half the control arm's weight and other components. These components are then (for calculation purposes) assumed to be connected to a vehicle with zero sprung weight. They are then put through the same dynamic loads. The weight transfer for cornering in the front would be equal to the total unsprung front weight times the G-Force times the front unsprung center of gravity height divided by the front track width. The same is true for the rear.

Sprung weight transfer

Sprung weight transfer is the weight transferred by only the weight of the vehicle resting on the springs, not the total vehicle weight. Calculating this requires knowing the vehicle's sprung weight (total weight less the unsprung weight), the front and rear roll center heights and the sprung center of gravity height (used to calculate the roll moment arm length). Calculating the front and rear sprung weight transfer will also require knowing the roll couple percentage.

The roll axis is the line through the front and rear roll centers that the vehicle rolls around during cornering. The distance from this axis to the sprung center of gravity height is the roll moment arm length. The total sprung weight transfer is equal to the G-force times the sprung weight times the roll moment arm length divided by the effective track width. The front sprung weight transfer is calculated by multiplying the roll couple percentage times the total sprung weight transfer. The rear is the total minus the front transfer.

Jacking forces

Jacking forces are the sum of the vertical force components experienced by the suspension links. The resultant force acts to lift the sprung mass if the roll center is above ground, or compress it if underground. Generally, the higher the roll center, the more jacking force is experienced.

Travel

Travel is the measure of distance from the bottom of the suspension stroke (such as when the vehicle is on a jack and the wheel hangs freely) to the top of the suspension stroke (such as when the vehicle's wheel can no longer travel in an upward direction toward the vehicle). Bottoming or lifting a wheel can cause serious control problems

or directly cause damage. "Bottoming" can be caused by the suspension, tires, fenders, etc. running out of space to move or the body or other components of the car hitting the road. The control problems caused by lifting a wheel are less severe if the wheel lifts when the spring reaches its unloaded shape than they are if travel is limited by contact of suspension members. Many off-road vehicles, such as desert racers, use straps called "limiting straps" to limit the suspensions downward travel to a point within safe limits for the linkages and shock absorbers. This is necessary, since these trucks are intended to travel over very rough terrain at high speeds, and even become airborne at times. Without something to limit the travel, the suspension bushings would take all the force when the suspension reaches "full droop", and it can even cause the coil springs to come out of their "buckets" if they are held in by compression forces only. A limiting strap is a simple strap, often nylon of a predetermined length, that stops the downward movement at a preset point before the theoretical maximum travel is reached. The opposite of this is the "bump-stop", which protects the suspension and vehicle (as well as the occupants) from violent "bottoming" of the suspension, caused when an obstruction (or hard landing) causes the suspension to run out of upward travel without fully absorbing the energy of the stroke. Without bump-stops, a vehicle that "bottoms out" will experience a very hard shock when the suspension contacts the bottom of the frame or body, which is transferred to the occupants and every connector and weld on the vehicle. Factory vehicles often come with plain rubber "nubs" to absorb the worst of the forces, and insulate the shock. A desert race vehicle, which must routinely absorb far higher impact forces, may be provided with pneumatic or hydro-pneumatic bump-stops. These are essentially miniature shock absorbers (dampeners) that are fixed to the vehicle in a location such that the suspension will contact the end of the piston when it nears the upward travel limit. These absorb the impact far more effectively than a solid rubber bump-stop will, essential because a rubber bump-stop is considered a "last-ditch" emergency insulator for the occasional accidental bottoming of the suspension; it is entirely insufficient to absorb repeated and heavy bottomings such as a high-speed off road vehicle encounters.

Damping

Damping is the control of motion or oscillation, as seen with the use of hydraulic gates and valves in a vehicles shock absorber. This may also vary, intentionally or unintentionally. Like spring rate, the optimal damping for comfort may be less than for control.

Damping controls the travel speed and resistance of the vehicle's suspension. An undamped car will oscillate up and down. With proper damping levels, the car will settle back to a normal state in a minimal amount of time. Most damping in modern vehicles can be controlled by increasing or decreasing the resistance to fluid flow in the shock absorber.

Camber control

Camber changes due to wheel travel, body roll and suspension system deflection or compliance. In general, a tire wears and brakes best at -1 to -2° of camber from vertical. Depending on the tire and the road surface, it may hold the road best at a slightly different angle. Small changes in camber, front and rear, can be used to tune handling. Some race cars are tuned with -2 ~ -7° camber depending on the type of handling desired and the tire construction. Oftentimes, too much camber will result in the decrease of braking performance due to a reduced contact patch size through excessive camber variation in the suspension geometry. The amount of camber change in bump is determined by the instantaneous front view swing arm (FVSA) length of the suspension geometry, or in other words, the tendency of the tire to camber inward when compressed in bump.

Roll center height

This is important to body roll and to front to rear roll stiffness distribution. However, the roll stiffness distribution in most cars is set more by the antiroll bars than the RCH. The height of the roll center is related to the amount of jacking forces experienced.

Instant center

Due to the fact that the wheel and tire's motion is constrained by the suspension links on the vehicle, the motion of the wheel package in the front view will scribe an imaginary arc in space with an "instantaneous center" of rotation at any given point along its path. The instant center for any wheel package can be found by following imaginary lines drawn through the suspension links to their intersection point.

A component of the tire's force vector points from the contact patch of the tire through instant center. The larger this component is, the less suspension motion will occur. Theoretically, if the resultant of the vertical load on the tire and the lateral force generated by it points directly into the instant center, the suspension links will not move. In this case, all weight transfer at that end of the vehicle will be geometric in nature. This is key information used in finding the force-based roll center as well.

In this respect the instant centers are more important to the handling of the vehicle than the kinematic roll center alone, in that the ratio of geometric to elastic weight transfer is determined by the forces at the tires and their directions in relation to the position of their respective instant centers.

No-dive and No-squat

Anti-dive and anti-squat are percentages and refer to the front diving under braking and the rear squatting under acceleration. They can be thought of as the counterparts for braking and acceleration as jacking forces are to cornering. The main reason for

the difference is due to the different design goals between front and rear suspension, whereas suspension is usually symmetrical between the left and right of the vehicle.

The method of determining the anti-dive or anti-squat depends on whether the suspension linkages react to the torque of braking and accelerating. For example, with inboard brakes and half-shaft driven rear wheels, the suspension linkages do not, but with outboard brakes and a swing-axle driveline, they do.

To determine the percentage of front suspension braking anti-dive for outboard brakes, it is first necessary to determine the tangent of the angle between a line drawn, in side view, through the front tire patch and the front suspension instant center, and the horizontal. In addition, the percentage of braking effort at the front wheels must be known. Then, multiply the tangent by the front wheel braking effort percentage and divide by the ratio of the center of gravity height to the wheelbase. A value of 50% would mean that half of the weight transfer to the front wheels, during braking, is being transmitted through the front suspension linkage and half is being transmitted through the front suspension springs.

For inboard brakes, the same procedure is followed but using the wheel center instead of contact patch center.

Forward acceleration anti-squat is calculated in a similar manner and with the same relationship between percentage and weight transfer. Anti-squat values of 100% and more are commonly used in dragracing, but values of 50% or less are more common in cars which have to undergo severe braking. Higher values of anti-squat commonly cause wheel hop during braking. It is important to note that, while the value of 100%...in either case...means that all of the weight transfer is being carried through the suspension linkage, this does not mean that the suspension is incapable of carrying additional loads (aerodynamic, cornering, etc.) during an episode of braking or forward acceleration. In other words, no "binding" of the suspension is to be implied.

Flexibility and vibration modes of the suspension elements

In modern cars, the flexibility is mainly in the rubber bushings. For high-stress suspensions, such as off-road vehicles, polyurethane bushings are available, which offer far more longevity under greater stresses.

Isolation from high frequency shock

For most purposes, the weight of the suspension components is unimportant, but at high frequencies, caused by road surface roughness, the parts isolated by rubber bushings act as a multistage filter to suppress noise and vibration better than can be done with only the tires and springs. (The springs work mainly in the vertical direction.)

Contribution to unsprung weight and total weight

These are usually small, except that the suspension is related to whether the brakes and differential(s) are sprung.

Space occupied

Designs differ as to how much space they take up and where it is located. It is generally accepted that MacPherson struts are the most compact arrangement for front-engined vehicles, where space between the wheels is required to place the engine.

Force distribution

The suspension attachment must match the frame design in geometry, strength and rigidity.

Air resistance (drag)

Certain modern vehicles have height adjustable suspension in order to improve aerodynamics and fuel efficiency. And modern formula cars, that have exposed wheels and suspension, typically use streamlined tubing rather than simple round tubing for their suspension arms to reduce drag. Also typical is the use of rocker arm, push rod, or pull rod type suspensions, that among other things, places the spring/damper unit inboard and out of the air stream to further reduce air resistance.

Cost

Production methods improve, but cost is always a factor. The continued use of the solid rear axle, with unsprung differential, especially on heavy vehicles, seems to be the most obvious example.

Springs and dampers

Most conventional suspensions use passive springs to absorb impacts and dampers (or shock absorbers) to control spring motions.

Some notable exceptions are the hydropneumatic systems, which can be treated as an integrated unit of gas spring and damping components, used by the French manufacturer Citroën and the hydrolastic, hydragas and rubber cone systems used by the British Motor Corporation, most notably on the Mini. A number of different types of each have been used:

Passive suspensions

Traditional springs and dampers are referred to as passive suspensions — most vehicles are suspended in this manner.

Springs



Pneumatic spring on a semitrailer

- Leaf spring – AKA Hotchkiss, Cart, or semi-elliptical spring
- Torsion beam suspension
- Coil spring
- Rubber bushing
- Air spring

Dampers or shock absorbers

The shock absorbers damp out the (otherwise resonant) motions of a vehicle up and down on its springs. They also must damp out much of the wheel bounce when the unsprung weight of a wheel, hub, axle and sometimes brakes and differential bounces up and down on the springiness of a tire. The regular bumps found on dirt roads

(nicknamed "corduroy", but properly corrugations or washboarding) are caused by this wheel bounce.

Semi-active and active suspensions

If the suspension is externally controlled then it is a semi-active or active suspension — the suspension is reacting to what are in effect "brain" signals. As electronics have become more sophisticated, the opportunities in this area have expanded.

For example, a hydropneumatic Citroën will "know" how far off the ground the car is supposed to be and constantly reset to achieve that level, regardless of load. It will *not* instantly compensate for body roll due to cornering however. Citroën's system adds about 1% to the cost of the car versus passive steel springs.

Semi-active suspensions include devices such as air springs and switchable shock absorbers, various self-levelling solutions, as well as systems like Hydropneumatic, Hydrolastic, and Hydragas suspensions. Mitsubishi developed the world's first production semi-active electronically controlled suspension system in passenger cars; the system was first incorporated in the 1987 Galant model. Delphi currently sells shock absorbers filled with a magneto-rheological fluid, whose viscosity can be changed electromagnetically, thereby giving variable control without switching valves, which is faster and thus more effective.

Fully active suspension systems use electronic monitoring of vehicle conditions, coupled with the means to impact vehicle suspension and behavior in real time to directly control the motion of the car. Lotus Cars developed several prototypes, from 1982 onwards, and introduced them to F1, where they have been fairly effective, but have now been banned. Nissan introduced a low bandwidth active suspension in circa 1990 as an option that added an extra 20% to the price of luxury models. Citroën has also developed several active suspension models. A recently publicised fully active system from Bose Corporation uses linear electric motors, i.e. solenoids, in place of hydraulic or pneumatic actuators that have generally been used up until recently. The most advanced suspension system is Active Body Control, introduced in 1999 on the top-of-the-line Mercedes-Benz CL-Class.

Several electromagnetic suspensions have also been developed for vehicles. Examples include the electromagnetic suspension of Bose, and the electromagnetic suspension developed by prof. Laurentiu Encica. In addition, the new Michelin wheel with embedded suspension working on a electromotor is also similar.

With the help of control system, various semi-active/active suspensions realize an improved design compromise among different vibrations modes of the vehicle, namely bounce, roll, pitch and warp modes. However, the applications of these advanced suspensions are constrained by the cost, packaging, weight, reliability, and/or the other challenges.

Interconnected suspensions

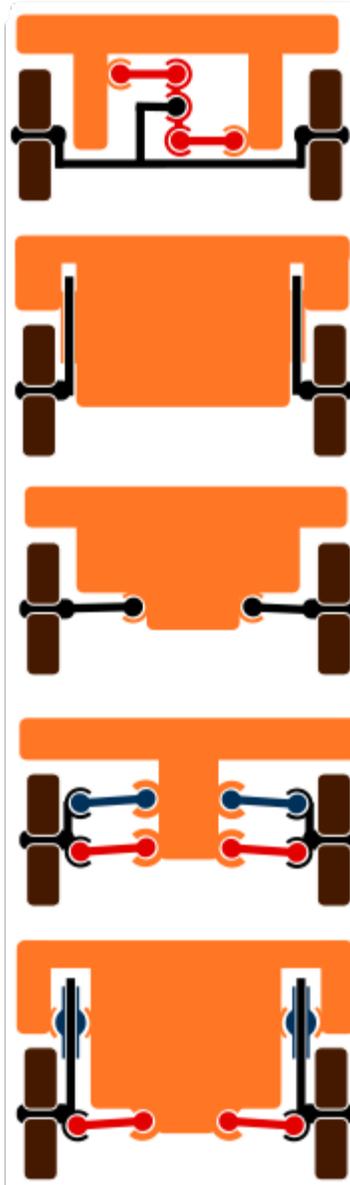
Interconnected suspension, unlike semi-active/active suspensions, could easily decouple different vehicle vibration modes in a passive manner. The interconnections can be realized by various means, such as mechanical, hydraulic and pneumatic. Anti-roll bars are one of the typical examples of mechanical interconnections, while it has been stated that fluidic interconnections offer greater potential and flexibility in improving both the stiffness and damping properties.

Considering the considerable commercial potentials of hydro-pneumatic technology (Corolla, 1996), interconnected hydropneumatic suspensions have also been explored in some recent studies, and their potential benefits in enhancing vehicle ride and handling have been demonstrated. The control system can also be used for further improving performance of interconnected suspensions. Apart from academic research, an Australian company, Kinetic, is having some success (WRC: 3 Championships, Dakar Rally: 2 Championships, Lexus GX470 2004 4x4 of the year with KDSS, 2005 PACE award) with various passive or semi-active systems, which generally decouple at least two vehicle modes (roll, warp (articulation), pitch and/or heave (bounce)) to simultaneously control each mode's stiffness and damping, by using interconnected shock absorbers, and other methods. In 1999, Kinetic was bought out by Tenneco.

Historically, the first mass production car with front to rear mechanical interconnected suspension was the 1948 Citroën 2CV. The suspension of the 2CV was extremely soft — it had low roll stiffness, but its pitch stiffness was increased by using an interconnected suspension. The leading arm / trailing arm swinging arm, fore-aft linked suspension system together with inboard front brakes had a much smaller unsprung weight than existing coil spring or leaf designs. The interconnection transmitted some of the force deflecting a front wheel up over a bump, to push the rear wheel down on the same side. When the rear wheel met that bump a moment later, it did the same in reverse, keeping the car level front to rear. The 2CV had a design brief to be able to be driven at speed over a ploughed field. It originally featured friction dampers and tuned mass dampers. Later models had tuned mass dampers at the front with telescopic dampers / shock absorbers front and rear.

Some of the last post-war Packard models also featured interconnected suspension. The original Mini and some more recent British Leyland models also featured interlinking, when fitted with Moulton's Hydrolastic or Hydragas suspensions.

Suspension Geometry



Common types seen from behind. From top to bottom: live axle with Watt bar, suspension like on a bike fork, swing axle, double wishbone, MacPherson. Some types are missing because trailing arm links are not presentable in this view and some types use elements which flex to some movements and are stiff to others and flexible elements are omitted for clarity.

Suspension systems can be broadly classified into two subgroups — dependent and independent. These terms refer to the ability of opposite wheels to move independently of each other.

A dependent suspension normally has a beam (a simple 'cart' axle) or (driven) live axle that holds wheels parallel to each other and perpendicular to the axle. When the

camber of one wheel changes, the camber of the opposite wheel changes in the same way (by convention on one side this is a positive change in camber and on the other side this a negative change). De Dion suspensions are also in this category as they rigidly connect the wheels together.

An *independent suspension* allows wheels to rise and fall on their own without affecting the opposite wheel. Suspensions with other devices, such as sway bars that link the wheels in some way are still classed as independent.

A third type is a *semi-dependent* suspension. In this case, the motion of one wheel does affect the position of the other but they are not rigidly attached to each other. A twist-beam rear suspension is such a system.

Dependent suspensions

Dependent systems may be differentiated by the system of linkages used to locate them, both longitudinally and transversely. Often both functions are combined in a set of linkages.

Examples of location linkages include:

- Satchell link
- Panhard rod
- Watt's linkage
- WOBLink
- Mumford linkage
- Leaf springs used for location (transverse or longitudinal)
 - Fully elliptical springs usually need supplementary location links and are no longer in common use
 - Longitudinal semi-elliptical springs used to be common and still are used in heavy-duty trucks and aircraft. They have the advantage that the spring rate can easily be made progressive (non-linear).
 - A single transverse leaf spring for both front wheels and/or both back wheels, supporting solid axles, was used by Ford Motor Company, before and soon after World War II, even on expensive models. It had the advantages of simplicity and low unsprung weight (compared to other solid axle designs).

In a front engine, rear-drive vehicle, dependent rear suspension is either "live axle" or deDion axle, depending on whether or not the differential is carried on the axle. Live axle is simpler but the unsprung weight contributes to wheel bounce.

Because it assures constant camber, dependent (and semi-independent) suspension is most common on vehicles that need to carry large loads as a proportion of the vehicle weight, that have relatively soft springs and that do not (for cost and simplicity

reasons) use active suspensions. The use of dependent front suspension has become limited to heavier commercial vehicles.



A rear independent suspension on an AWD car.

Semi-independent suspension

In a semi-independent suspensions, the wheels of an axle are able to move relative to one another as in an independent suspension but the position of one wheel has an effect on the position and attitude of the other wheel. This effect is achieved via the twisting or deflecting of suspension parts under load. The most common type of semi-independent suspension is the twist beam.

- Twist beam

Independent suspension

The variety of independent systems is greater and includes:

- Swing axle
- Sliding pillar
- MacPherson strut/Chapman strut
- Upper and lower A-arm (double wishbone)

- multi-link suspension
- semi-trailing arm suspension
- swinging arm
- leaf springs
 - Transverse leaf springs when used as a suspension link, or four quarter elliptics on one end of a car are similar to wishbones in geometry, but are more compliant. Examples are the front of the original Fiat 500, the Panhard Dyna Z and the early examples of Peugeot 403 and the back of the AC Ace and AC Aceca.

Because the wheels are not constrained to remain perpendicular to a flat road surface in turning, braking and varying load conditions, control of the wheel camber is an important issue. Swinging arm was common in small cars that were sprung softly and could carry large loads, because the camber is independent of load. Some active and semi-active suspensions maintain the ride height, and therefore the camber, independent of load. In sports cars, optimal camber change when turning is more important.

Wishbone and multi-link allow the engineer more control over the geometry, to arrive at the best compromise, than swing axle, MacPherson strut or swinging arm do; however the cost and space requirements may be greater. Semi-trailing arm is in between, being a variable compromise between the geometries of swinging arm and swing axle.

Armoured fighting vehicle suspension



This Grant I tank's suspension has road wheels mounted on wheel trucks, or *bogies*.

Military AFVs, including tanks, have specialized suspension requirements. They can weigh more than seventy tons and are required to move at high speed over very rough ground. Their suspension components must be protected from land mines and antitank weapons. Tracked AFVs can have as many as nine road wheels on each side. Many wheeled AFVs have six or eight wheels, to help them ride over rough and soft ground.

The earliest tanks of World War I had fixed suspension with no movement whatsoever. This unsatisfactory situation was improved with leaf spring or coil spring suspensions adopted from agricultural, automotive or railway machinery, but even these had very limited travel.

Speeds increased due to more powerful engines, and the quality of ride had to be improved. In the 1930s, the Christie suspension was developed, which allowed the use of coil springs inside a vehicle's armored hull, by changing the direction of force deforming the spring, using a bell crank. Horstmann suspension was a variation which used a combination of bell crank and exterior coil springs, in use from the 1930s to the 1990s.

By World War II the other common type was torsion-bar suspension, getting spring force from twisting bars inside the hull — this had less travel than the Christie-type, but was significantly more compact, allowing more space inside the hull, with consequent possibility to install larger turret rings and thus a heavier main armament. The torsion-bar suspension, sometimes including shock absorbers, has been the dominant heavy armored vehicle suspension since World War II.

Automotive Suspension Design

Automotive suspension design is an aspect of automotive engineering, concerned with designing the suspension for cars and trucks.

The process entails

- selecting appropriate vehicle level targets
- selecting a system architecture
- choosing the location of the 'hard points', or theoretical centres of each ball joint or bushing
- selecting the rates of the bushings
- analysing the loads in the suspension
- designing the spring rates
- designing shock absorber characteristics
- designing the structure of each component so that it is strong, stiff, light, and cheap
- analysing the vehicle dynamics of the resulting design

Since the 1990s the use of multibody simulation and finite element software has made this series of tasks more straightforward.

Vehicle level targets

A partial list would include:

- maximum steady state lateral acceleration (in understeer mode)
- roll stiffness (degrees per g of lateral acceleration)
- ride frequencies
- lateral load transfer percentage distribution front to rear
- Roll moment distribution front to rear
- ride heights at various states of load
- Understeer gradient
- Turning circle
- Ackermann
- Jounce travel
- Rebound travel

Once the overall vehicle targets have been identified they can be used to set targets for the two suspensions. For instance, the overall understeer target can be broken down into contributions from each end using a Bundorf analysis.

System architecture

Typically a vehicle designer is operating within a set of constraints. The suspension architecture selected for each end of the vehicle will have to obey those constraints. For both ends of the car this would include the type of spring, location of the spring, and location of the shock absorbers.

For the front suspension the following need to be considered

- the type of suspension (MacPherson strut or double wishbone suspension)
- type of steering actuator (rack and pinion or recirculating ball)
- location of the steering actuator in front of, or behind, the wheel centre

For the rear suspension there are many more possible suspension types, in practice.

Hardpoints

The hardpoints control the static settings and the kinematics of the suspension.

The static settings are

- Toe
- Camber
- Caster
- Roll center height at design load
- Mechanical (or caster) trail
- Anti-dive and anti-squat
- Kingpin Inclination
- Scrub radius
- Spring and shock absorber motion ratios

The kinematics describe how important characteristics change as the suspension moves, typically in roll or steer. They include

- Bump Steer
- Roll Steer
- Tractive Force Steer
- Brake Force Steer
- Camber gain in roll
- Caster gain in roll
- Roll centre height gain
- Ackerman change with steering angle

- Track gain in roll

The analysis for these parameters can be done graphically, or by CAD, or by the use of kinematics software.

Compliance analysis

The compliance of the bushings, the body, and other parts modify the behaviour of the suspension. In general it is difficult improve the kinematics of a suspension using the bushings, but one example where it does work is the toe control bush used in Twist-beam rear suspensions. More generally, modern cars suspensions include an NVH bush. This is designed as the main path for the vibrations and forces that cause road noise and impact noise, and is supposed to be tunable without affecting the kinematics too much;

Loads

Once the basic geometry is established the loads in each suspension part can be estimated. This can be as simple as deciding what a likely maximum load case is at the contact patch, and then drawing a Free body diagram of each part to work out the forces, or as complex as simulating the behaviour of the suspension over a rough road, and calculating the loads caused. Often loads that have been measured on a similar suspension are used instead - this is the most reliable method.

Detailed design of arms

The loads and geometry are then used to design the arms and spindle. Inevitably some problems will be found in the course of this that force compromises to be made with the basic geometry of the suspension.

Chapter 3

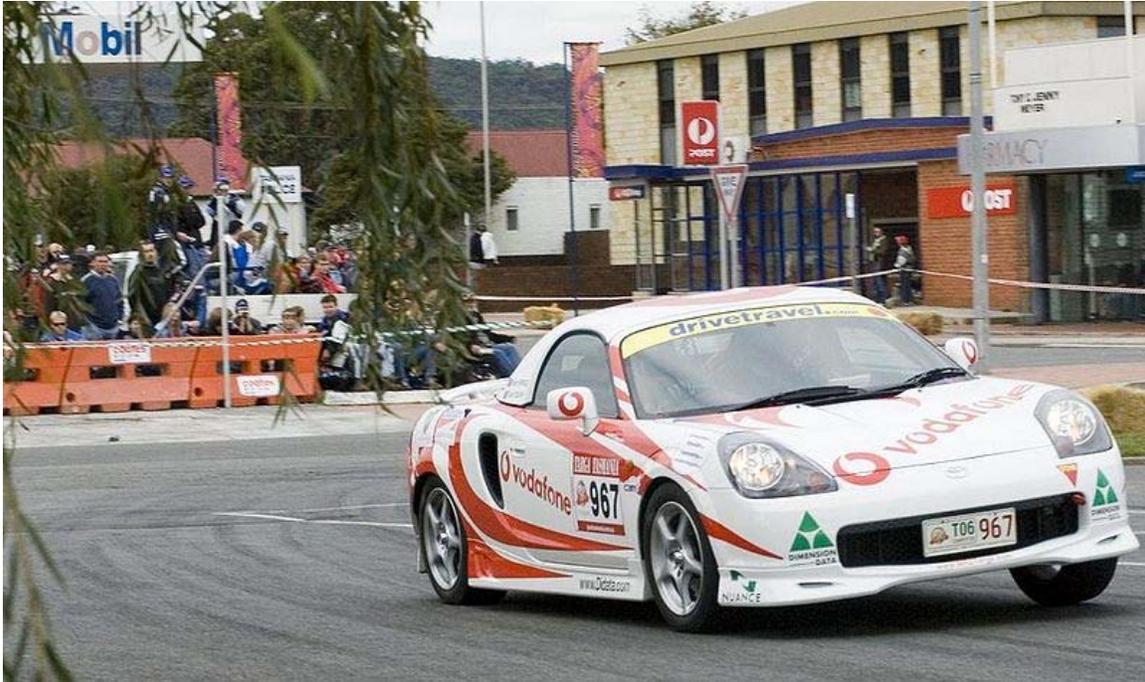
Weight Transfer



Camaro performing a wheelie during drag racing.



A motorcyclist performing a stoppie.



A Toyota MR2 leaning to the outside of a turn.

Weight transfer and **load transfer** are two expressions used somewhat confusingly to describe two distinct effects: the change in load borne by different wheels of even perfectly rigid vehicles during acceleration, and the change in center of mass (CoM) location relative to the wheels because of suspension compliance or cargo shifting or sloshing. In the automobile industry, **weight transfer** customarily refers to the change in load borne by different wheels during acceleration. This is more properly referred to as **load transfer**, and that is the expression used in the motorcycle industry, while **weight transfer** on motorcycles, to a lesser extent on automobiles, and cargo movement on either is due to a change in the CoM location relative to the wheels.

Load transfer

In wheeled vehicles, **load transfer** is the measurable change of load borne by different wheels during acceleration (both longitudinal and lateral). This includes braking, and deceleration (which is an acceleration at a negative rate). No motion of the centre of gravity (CoG) relative to the wheels is necessary, and so load transfer may be experienced by vehicles with no suspension at all. Load transfer is a crucial concept in understanding vehicle dynamics. The same is true in bikes, though only longitudinally.

Cause

The major forces that accelerate a vehicle occur at the tires' contact patches. Since these forces are not directed through the vehicle's CoG, one or more moments are generated whose forces are the tyres traction forces at pavement level, the other one (equal but opposed) is the mass inertia located at (CoG) and the arm is the distance from pavement surface to CoG. It is these moments that cause variation in the load distributed between the tires. Often this is interpreted by the casual observer as a pitching or rolling motion of the vehicles body. A perfectly rigid vehicle without suspension that would not exhibit pitching or rolling of the body still undergoes load transfer. However, the pitching and rolling of the body adds some (small) weight transfer due to the (small) CoG horizontal displacement with respect to the wheels axis suspension vertical travel and also due to deformation of the tires i.e. contact patch displacement relative to wheel.

Lowering the CoG towards the ground is one method of reducing load transfer. As a result load transfer is reduced in both the longitudinal and lateral directions. Another method of reducing load transfer is by increasing the wheel spacings. Increasing the vehicle's wheel base (length) reduces longitudinal load transfer while increasing the vehicle's track (width) reduces lateral load transfer. Most high performance automobiles are designed to sit as low as possible and usually have an extended wheel base and track.

Weight transfer

Weight transfer involves the *actual* (relatively small) movement of the vehicle CoG relative to the wheel axes due to displacement of the chassis as the suspension complies, or of cargo or liquids within the vehicle, which results in a redistribution of the total vehicle load between the individual tires.

Center of gravity

Weight transfer occurs as the vehicle's center of gravity (CoG) shifts during automotive maneuvers. Acceleration causes the sprung mass to rotate about a geometric axis resulting in relocation of the CoG. Front-back weight transfer is proportional to the change in the longitudinal location of the center of gravity to the vehicle's wheelbase, and side-to-side weight transfer (summed over front and rear) is proportional to the ratio of the change in the center of gravity's lateral location to the vehicle's track.

Liquids, such as fuel, readily flow within their containers, causing changes in the vehicle's CoG. As fuel is consumed, not only does the position of the CoG change, but the total weight of the vehicle is also reduced.

By way of example, when a vehicle accelerates, a weight transfer toward the rear wheels can occur. An outside observer might witness this as the vehicle visibly leans

to the back, or squats. Conversely, under braking, weight transfer toward the front of the car can occur. Under hard braking it might be clearly visible even from inside the vehicle as the nose dives toward the ground (most of this will be due to load transfer). Similarly, during changes in direction (lateral acceleration), weight transfer to the outside of the direction of the turn can occur.

Weight transfer is generally of far less practical importance than load transfer, for cars and SUVs at least. For instance in a 0.9g turn, a car with a track of 1650 mm and a CG height of 550 mm will see a load transfer of 30% of the vehicle weight, that is the outer wheels will see 30% more load than before, and the inners 30% less. Total available grip will drop by around 3% as a result of this load transfer. At the same time, the CG of the vehicle will typically move laterally and vertically, relative to the contact patch by no more than 30 mm, leading to a weight transfer of less than 2%, and a corresponding reduction in grip of 0.01%.

Traction

Load transfer causes the available traction (engineering) at all four wheels to vary as the car brakes, accelerates, or turns. This bias to one pair of tires doing more 'work' than the other pair results in a net loss of total available traction. The net loss can be attributed to the phenomenon known as tire load sensitivity.

An exception is during positive acceleration when the engine power is driving two or fewer wheels. In this situation where all the tires are not being utilized load transfer can be advantageous. As such, the most powerful cars are almost never front wheel drive, as the acceleration itself causes the front wheels' traction to decrease. This is why sports cars usually have either rear wheel drive or all wheel drive (and in the all wheel drive case, the power tends to be biased toward the rear wheels under normal conditions).

Rollover

If (lateral) load transfer reaches the tire loading on one end of a vehicle, the inside wheel on that end will lift, causing a change in handling characteristic. If it reaches half the weight of the vehicle it will start to roll over. Some large trucks will roll over before skidding, while passenger vehicles and small trucks usually roll over only when they leave the road. Fitting racing tires to a tall or narrow vehicle and then driving it hard may lead to rollover.

Chapter 4

TorqueFlite

	TorqueFlite
Manufacturer	Chrysler Corporation
Production	1956–
Predecessor	PowerFlite
Class	3- or 4-speed automatic

TorqueFlite (also spelled Torqueflite) was the trademarked name of Chrysler Corporation's three-speed automatic transmission, which was introduced late in the 1956 model year. TorqueFlite was introduced on the heels of the company's two-speed PowerFlite automatic, which made its debut in 1954. In the 1990s, the TorqueFlite name was dropped and the transmissions were referred to by a model number referring to their torque rating and gear set, although some models remained completely unchanged.

History

The first Torqueflites provided three speeds forward plus reverse. Gear ratios were 2.45:1 in first, 1.45 in second, and 1.00 in third. The transmission was controlled by a series of pushbuttons located on the vehicle's dashboard. The buttons were generally at the extreme driver's side end of the dash, i.e., the left in left-hand drive vehicles, and the right in right-hand drive ones. However, this was not always the case; the 1962 Dodge Phoenix, a right-hand drive export model sold in Australia and South Africa, used the U.S. 1962 Plymouth Valiant instrument cluster assembly, into the left end of which were integrated the transmission pushbuttons. Button arrangement varied by vehicle model and year; sequence was Reverse, Neutral, Drive, Second, and First, from top to bottom with vertically-arrayed buttons, from left to right with horizontally-arrayed buttons, and clockwise starting at upper left with clustered buttons.

A parking lock was not provided until the advent of the aluminum-case Torqueflites in 1960 (standard-duty A-904) and 1962 (heavy-duty A-727), at which point a lever was added adjacent to the pushbuttons: Throwing the lever to the "Park" position placed the car into Neutral and engaged a lock pawl on the transmission's output shaft. Throwing the park lever out of "Park" position unlocked the shift buttons so that a driving range could be selected. The buttons were replaced by conventional steering column- or floor-mounted shift levers in all automatic Chrysler-built vehicles for the 1965 model year, though floor levers were available in certain sporty 1964 models.

Like a vehicle with a General Motors Hydramatic, a vehicle with a Torqueflite transmission starts out in first gear when the Drive or Second position is selected. This is in contrast to vehicles with several automatics from Ford and Borg-Warner, which start out in second rather than first if the Second position is selected.

1962 brought the addition of a canister-style fluid filter installed in the cooler line. For 1964, the canister filter was eliminated, and the transmission's internal intake screen was replaced by an efficient Dacron filter. Fluid life starting in 1964 was extended from 12,000 mi (19,000 km) to 50,000 mi (80,000 km), providing justification for the deletion of the drain plug from the oil pan.

For 1966, the twin-cable shift and park control mechanism (a holdover from the push-button operation) was replaced by a solid shift control linkage consisting of a series of pushrods, rotating rods and levers. The rear pump was eliminated, which simplified and cost-reduced the transmission but rendered push-starting impossible; Chrysler engineers reasoned that improved electrical and fuel systems reduced the need to push-start vehicles, and safety concerns weighed against doing so. The gated shift quadrants also permitted the deletion of the reverse safety blocker valve which, in TorqueFlites made through 1965, had shifted the transmission harmlessly into Neutral if the Reverse position were selected with the vehicle moving forward above approximately 3 mph (4.8 km/h).

In 1968, part-throttle downshift functionality was added to A-904 transmissions used with 6-cylinder engines. This feature permitted the transmission to shift from third to second gear in response to moderate accelerator pressure. Previously, an automatic 3-2 downshift occurred only if the driver pushed the accelerator to the floor. This change was made to maintain acceptable in-town performance with taller final-drive ratios in the rear axle — 2.76:1 rear axle gears were being furnished in applications previously equipped with 2.93:1 or 3.23:1 gearsets. Part-throttle downshift functionality was extended to V8 A-904s in 1969, and to most A-727 transmissions in 1970 to 1971.

In 1978, most Torqueflite transmissions gained a lockup torque converter clutch to mechanically connect the converter's impeller and turbine, eliminating slip for better highway fuel economy. This addition required the removal of the torque converter drain plug.

For 1980, a wide-ratio gearset was released for the A904, A998 and A999, with 2.74:1 in first, 1.54 in second, and 1.00 in third.

Torqueflite was an available option or standard equipment, depending on model and year, on all Chrysler products: Plymouth, Dodge, DeSoto, Chrysler and Imperial. It was also used by American Motors beginning in 1972, where it was named **TorqueCommand**, as well as by Jeep, International Harvester, Maserati Quattroporte, Monteverdi and Bristol. When installed in Dodge trucks and vans, the transmission was marketed as **LoadFlite**.

In the 1990s, the transmissions were renamed, however the Torqueflite remains the basis of all current Chrysler designed transmissions. Jeep used several other manufacturers' transmissions until 1997, and Mercedes-Benz uses its own design identified by the number "722". Also several of the pickup lines now use transmissions from various sources.

Nomenclature

Torqueflite transmissions and transaxles made through 1991 were assigned arbitrary designations consisting of the letter "A" followed by three digits. 1992 and later units have four-character designations in which the first through fourth characters indicate, respectively, the number of forward speeds, torque capacity, drive type or transaxle orientation, and control system:

Forward speeds	Torque capacity	Drive type	Control
3 or 4	1 (low) to 9 (high)	R (Rear wheel) T (Transverse) A (All-wheel)	H (Hydromechanical) E (Electronic)

Technology

Torqueflites use a torque converter and the **Simpson Gearset**, two identical planetary gearsets sharing a common sun gear. Chrysler Corporation licensed this gearset from Simpson in 1955.

Rear-wheel drive transmissions

A488

The original TorqueFlite was designated **A488**, with a cast iron case and no parking pawl.

A500

The **A500**, later 40RH/42RH (hydraulic) and 40RE/42RE/44RE (electronic), was an A904 derivative used in trucks and vans. Introduced in the 1989 model year on a limited basis, it was the first light-duty Chrysler four-speed automatic and was placed behind the 3.9 L and 5.2 L engines for light-duty purposes. A tailshaft overdrive unit was bolted to the rear of the case to provide a total of four forward speeds, and was replaced by the 42RLE in 2004.

Gear ratios:

1	2	3	4	R
2.74	1.54	1.00	0.69	2.21

Applications:

- 1989-2001 Dodge Ram pickup 150/1500 V6/V8(2WD)
- 1989-2003 Dodge Ram Van B150/B250 V6/V8
- 1989-2003 Dodge Dakota
- 1993-2004 Jeep Grand Cherokee I6
- 1996-1998 Jeep Grand Cherokee 5.2 V8

A518

The **A518**, later 46RH (hydraulic controlled governor pressure) and 46RE (electronic controlled governor pressure), is an A727 derivative with overdrive. Starting in the early 1990s, it was used in trucks and vans. The overdrive fourth gear ratio is 0.69:1.

Gear ratios:

1	2	3	4	R
2.45	1.45	1.00	0.69	2.35

Applications:

- Dodge Ram pickup and vans 1500/2500/3500 V8 engines (DGT)
- Dodge Dakota *R/T* (1998-2003)
- Jeep Grand Cherokee 1998 5.9L
- Jeep Grand Cherokee 1993-1995 5.2 V8

A618

The **A618**, later 47RH (hydraulic controlled governor pressure) and 47RE (electronic controlled governor pressure), is a heavier-duty version of A518. It was used in trucks and vans starting in the mid-1990s. While currently used with some internal changes

when coupled to the 5.9 L Cummins Turbo-Diesel and the 8.0 L V-10 applications, it's still a 727 with overdrive and stronger internal parts. It has an input torque rating of 450 lb·ft (610 N·m).

Gear ratios:

1	2	3	4	R
2.45	1.45	1.00	0.69	2.21

Applications:

- Dodge Ram pickups 2500/3500 ISB Diesel and iron V-10 (DGP)
- Dodge Ram SRT-10 (DGP)f

A727

The A488 was replaced in 1962 with the **A727** (later 36RH and 37RH), with an aluminum case to reduce weight by about 60 lb (27 kg). The A727 incorporated a parking pawl and various internal improvements, and used a 10.75 in (27.3 cm) or 11.75 in (29.8 cm) torque converter. The heavier-duty A727 Torqueflites became — and remain — popular for drag racing and monster truck applications because of their controllability and strength.

- 1962-1978 361 , 383 , 400 B-Motor V8
- 1962-1978 413 , 426 wedge , 440 RB-V8
- 1964-1965 426 Hemi Super Stock
- 1966-1971 426 "Street" Hemi
- 1962-1966 318 "A" "Poly" V8
- 1968-1973 340
- 1971-1978 360
- H.D. 225 Slant Six (Police , Taxi , Light-Duty Pickups , "A" Van , "B" Van)

was known as "A-727-RG" (Raised-deck "G" Motor)

- 1972-c.1978 AMC 304 , 360 , 401 V8 "Torque-Command 8"

A904

For standard-duty applications in smaller and lighter vehicles with 6-cylinder or small V8 engines, the compact **A904** (later 30RH) was introduced in 1960. This transmission used a 10.75 in (27.3 cm) torque converter. There was also a smaller version of this transmission used in the Dodge Colt/Plymouth Champ cars made by Mitsubishi in Japan. This smaller transmission used a 10 in (25 cm) torque converter.

Uses:

- 1960-1976 170 , 198 , 225 Slant Six
- 1964-1969 273 LA-V8
- 1967-1978 318 LA-V8
- 1975-1978 360 2Bbl LA-V8
- 1972-c.1978 AMC I-6 "Torque-Command 6"

A998

The **A998** (later, 31RH) was a medium-duty, wide-ratio version of the small-frame A904 transmission for use with medium-power V8 engines and the 3.9 L V6 engine.

The 998 was equipped with four direct friction plates.

These automatics had lower first and second gear ratios to allow the lower-powered engines to provide better acceleration without sacrificing highway fuel economy.

A999

The **A999** (later 32RH) was a heavier-duty, wide-ratio version of the small-frame A904 transmission for use with medium-power V8 engines and the 3.9 L V6 engine.

The 999 was equipped with four or five direct friction plates.

These automatics had lower first and second gear ratios to allow the lower-powered engines to provide better acceleration without sacrificing highway fuel economy.

Uses:

- Jeep Wrangler TJ's with the 4.0 straight 6

30RH

A renamed light-duty A904.

31RH

A renamed medium-duty A998.

32RH

A renamed heavier medium-duty A999.

40RH

A renamed light-duty A500. A904 with overdrive and hydraulic control.

42RH

A renamed medium-duty A500. A998 with overdrive and hydraulic control.

44RE

A renamed heavy-duty A500. A999 with overdrive and electrical control.

46RH

A renamed A518. A727 with overdrive and hydraulic control.

Applications:

- 1994-1995 Dodge Ram 2500/3500 V8
- 1995 (Jeep Grand Cherokee 5.2)

46RE

A renamed second-generation A518. A727 with overdrive and electrical control.

Applications:

- 1996 Dodge Dakota V8
- 1996-2002 Dodge Ram 1500/2500/3500 V8
- 1998-2000 Dodge Durango 5.9L V8 (4WD or 2WD)
- 1998 Jeep Grand Cherokee 5.9L V8 (4WD or 2WD)

47RH

A renamed A618 and hydraulic control.

Applications:

- 1994-1995 Dodge Ram 2500/3500 Diesel/V10

47RE

A renamed second-generation A618. A heavy-duty A727 with overdrive and electrical control.

Applications:

- 1996-2002 Dodge Ram 2500/3500 Diesel/V10

48RE

The **48RE** is an electronically-governed, four-speed heavy-duty overdrive automatic transmission, stronger than its predecessor, the 47-series.

Gear ratios:

1	2	3	4	R
2.45	1.45	1.00	0.69	2.21

Applications:

- 2003-2004 Dodge Ram 2500/3500 ISB Diesel
- 2003-2004 Dodge Ram 2500/3500 HO ISB Diesel
- 2004-2007 Dodge Ram 2500/3500 600/610 Diesel
- 2004-2006 Dodge Ram SRT-10

Front-wheel drive transaxles

The A404, A413, A470, and A670 are front wheel drive transaxle derivatives of the A904 Torqueflite.

In the late 1970s, Chrysler designed the **A404** TorqueFlite three-speed automatic transaxle for its front wheel drive Dodge Omni and Plymouth Horizon subcompact cars. This transaxle would be upgraded in the 1980s into the **A413** and **A670** units, which were progressively heavier-duty, for Chrysler's K-cars and their derivatives, including the minivans. The four-speed Ultradrive electronic four-speed automatic transaxle would eventually replace it, but the three-speed lasted for more than a decade after the 1989 debut of the four-speed unit.

A404

The light-duty A404 was used with the smallest straight-4 engines from Chrysler, commonly the 1.7 L Volkswagen unit.

A413 or 31TH

The A404 was strengthened to become the **A413** (later **31TH**) in 1981. This was used with Chrysler's 2.2 and 2.5 L K-car engines. It was available both with and without a

lockup torque converter. This transmission was also used in the Dodge Neon from 1995-2001. The A413 is broadly similar in concept to Ford's *ATX* three-speed unit.

A415

The **A415** was developed for the 1.6 L Simca 1100 engine, but was not released for series production.

A470

The **A470** was a strengthened version of the transaxle used with the 2.6 L *Mitsubishi Astron engine* in the K-cars from 1981-1985 and minivans from 1984 through 1987.

A670

The highest-specification three-speed transaxle was the **A670**. It was used with the 3.0 L *Mitsubishi V6* engine in Chrysler's cars and minivans from 1987-2000.

Gear ratios:

1	2	3	R	Final
2.69	1.55	1.00	2.10	3.02

Chapter 5

Automotive Hemming & Automotive Aerodynamics

Automotive Hemming

Hemming (Automotive) Hemming is a technology used by the automotive industry to join inner and outer closure panels together (hoods, doors, tailgates, etc.). It is the process of bending/folding the flange of the outer panel over the inner one. The accuracy of the operation affects significantly the appearance of the car's outer surfaces and is therefore a critical factor in the final quality of a finished vehicle.

Hemming Processes

Press Hemming

Hemming presses are widely used in automotive manufacturing for hemming of sheet-metal body components. The process uses traditional hydraulically operated 'stamping presses' to hem closure parts and being the last forming process in stamping, it determines the external quality of automotive outer parts such as doors, hood and trunk-lid.

Hemming press features and benefits

- Die storage systems
- Fully automatic die-changing systems
- Pressing capacity typically 150 or 180 tons
- Large panel size capacity
- More than one part can be produced on same line

Hemming Press Limitations

- Restricted to flat un-complicated panel profiles
- High Cost

Table Top Hemming

Tabletop hemming machines are utilised for the manufacture of medium to high production volumes, with the ability to achieve cycle times as low as 15 seconds.

Table Top features and benefits

- Optimum panel quality guaranteed through the hemming principle of the closed ring (

Table Top Limitations

- Dedicated to one panel

Robot (Roller Hemming)

Robot hemming uses a standard Industrial Robot integrated with a roller hemming head to provide a flexible solution to closure manufacture. The flange of the outer panel is bent over the inner panel in progressive steps by means of the roller hemming head. The process allows the advantage of using the robot controlled hemming head to hem several different components in a single cell. Minor changes and modifications to panel hemming conditions can also be accommodated allowing a quick and cost-effective reaction.

The robot can also be used for other tasks for example, by equipping it with a tool changing system. This will allow it to also operate dispensing equipment for adhesives and sealants, or a gripper which will enable it to carry out panel manipulation within the assembly cell.

Robot Hemming features and benefits

- The ideal solution for low to medium volume production demands
- Flexibility as robot can hem various panels and can perform other tasks with economical implementation of panel changes
- Simple and quiet in operation
- Low cost simple hem roller tooling and use of standard Industrial robot
- Reduced mechanical effort for tryout
- Flexible production with regard to different types and variants

Automotive Aerodynamics



A truck with added bodywork on top of the cab to reduce drag.

Automotive aerodynamics is the study of the aerodynamics of road vehicles. The main concerns of automotive aerodynamics are reducing drag (though drag by wide wheels is dominating most cars), reducing wind noise, minimizing noise emission, and preventing undesired lift forces and other causes of aerodynamic instability at high speeds. For some classes of racing vehicles, it may also be important to produce desirable downwards aerodynamic forces to improve traction and thus cornering abilities.

An aerodynamic automobile will integrate the wheel arcs and lights in its shape to have a small surface. It will be streamlined, for example it does not have sharp edges crossing the wind stream above the windshield and will feature a sort of tail called a fastback or Kammback or liftback. Note that the Aptera 2e, the Loremo, and the Volkswagen 1-litre car try to reduce the area of their back. It will have a flat and smooth floor to support the Venturi effect and produce desirable downwards aerodynamic forces. The air that rams into the engine bay, is used for cooling, combustion, and for passengers, then reaccelerated by a nozzle and then ejected under the floor. For mid and rear engines air is decelerated and pressurized in a diffuser,

loses some pressure as it passes the engine bay, and fills the slipstream. These cars need a seal between the low pressure region around the wheels and the high pressure around the gearbox. They all have a closed engine bay floor. The suspension is either streamlined (Aptera) or retracted. Door handles, the antenna, and roof rails can have a streamlined shape. The side mirror can only have a round fairing as a nose. Air flow through the wheel-bays is said to increase drag (German source) though race cars need it for brake cooling and a lot of cars emit the air from the radiator into the wheel bay.

Automotive aerodynamics differs from aircraft aerodynamics in several ways. First, the characteristic shape of a road vehicle is much less streamlined compared to an aircraft. Second, the vehicle operates very close to the ground, rather than in free air. Third, the operating speeds are lower (and aerodynamic drag varies as the square of speed). Fourth, a ground vehicle has fewer degrees of freedom than an aircraft, and its motion is less affected by aerodynamic forces. Fifth, passenger and commercial ground vehicles have very specific design constraints such as their intended purpose, high safety standards (requiring, for example, more 'dead' structural space to act as crumple zones), and certain regulations. Roads are also much worse (smoothness, debris) than the average airstrip. Lastly, car drivers are vastly under-trained compared to pilots, and usually will not drive to maximize efficiency.

Automotive aerodynamics is studied using both computer modelling and wind tunnel testing. For the most accurate results from a wind tunnel test, the tunnel is sometimes equipped with a rolling road. This is a movable floor for the working section, which moves at the same speed as the air flow. This prevents a boundary layer forming on the floor of the working section and affecting the results. An example of such a rolling road wind tunnel is Wind Shear's Full Scale, Rolling Road, Automotive Wind Tunnel built in 2008 in Concord, North Carolina.

Drag coefficient

Drag coefficient (C_d) is a commonly published rating of a car's aerodynamic smoothness, related to the shape of the car. Multiplying C_d by the car's frontal area gives an index of total drag. The result is called *drag area*, and is listed below for several cars. The width and height of curvy cars lead to gross overestimation of frontal area. These numbers use the manufacturer's frontal area specifications from the

Mayfield Company Homepage.

Some examples:

Drag area ($C_d \times$ Ft ²)	Year Automobile
3.95	1996 GM EV1
5.10	1999 Honda Insight

5.40	1989 Opel Calibra
5.54	1980 Ferrari 308 GTB
5.61	1993 Mazda RX-7
5.61	1993 McLaren F1
5.63	1991 Opel Calibra
5.64	1990 Bugatti EB110
5.71	1990 Honda CRX
5.74	2002 Acura NSX
5.76	1968 Toyota 2000GT
5.88	1990 Nissan 240SX
5.86	2001 Audi A2 1.2 TDI 3L
5.92	1994 Porsche 911 Speedster
5.95	1994 McLaren F1
6.00	1970 Lamborghini Miura S
6.00	1992 Subaru SVX
6.06	2003 Opel Astra Coupe Turbo
6.08	2008 Nissan GTR
6.13	1991 Acura NSX
6.15	1989 Suzuki Swift GT
6.17	1995 Lamborghini Diablo
6.24	2004 Toyota Prius
6.27	1986 Porsche 911 Carrera
6.27	1992 Chevrolet Corvette
6.35	1999 Lotus Elise
6.77	1995 BMW M3
6.79	1993 Corolla DX
6.81	1989 Subaru Legacy
6.96	1988 Porsche 944 S
7.02	1992 BMW 325I
7.10	Saab 900
7.13	2007 SSC Ultimate Aero
7.48	1993 Chevrolet Camaro Z28
7.57	1992 Toyota Camry
8.70	1990 Volvo 740 Turbo
8.71	1991 Buick LeSabre Limited
9.54	1992 Chevy Caprice Wagon
10.7	1992 Chevrolet S-10 Blazer
11.63	1991 Jeep Cherokee
13.10	1990 Range Rover Classic

13.76	1994 Toyota T100 SR5 4x4
14.52	1994 Toyota Land Cruiser
17.43	1992 Land Rover Discovery
18.03	1992 Land Rover Defender 90
18.06	1993 Hummer H1
20.24	1993 Land Rover Defender 110
26.32	2006 Hummer H2

Relationship to velocity

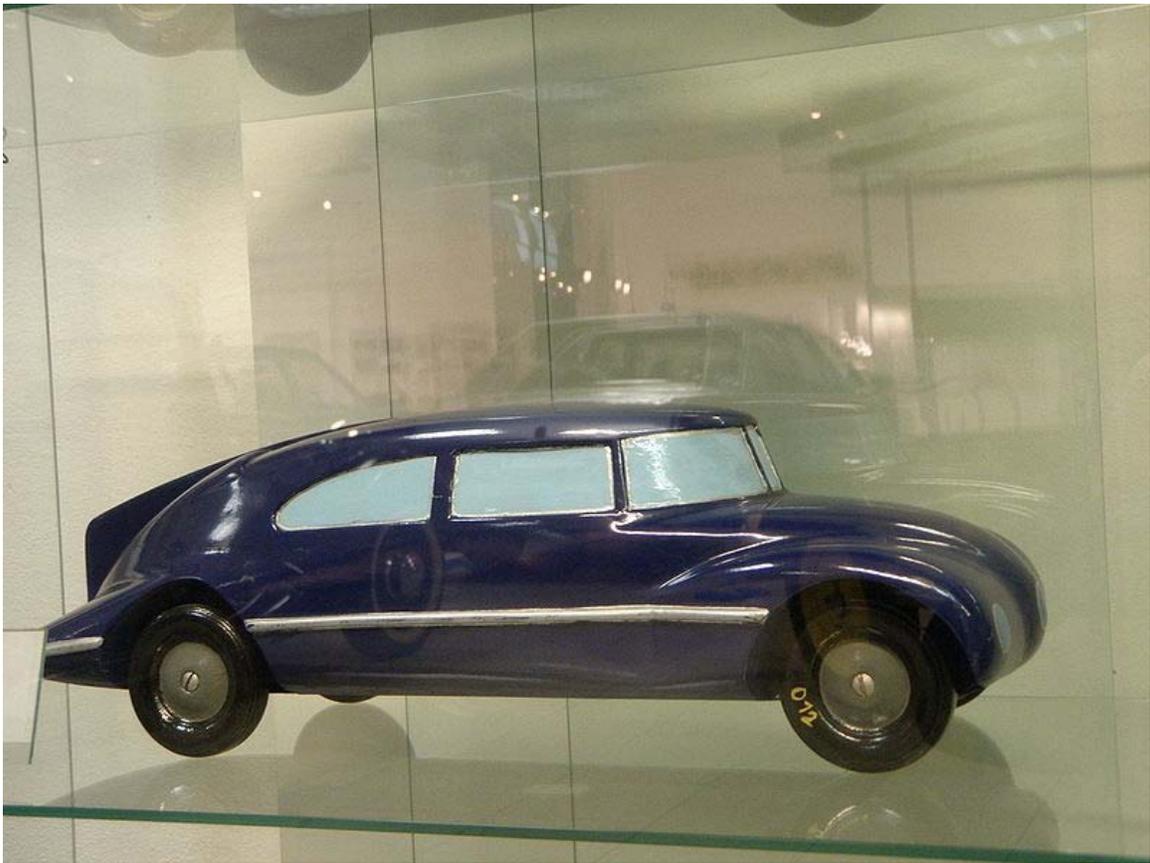
The frictional force of aerodynamic drag increases significantly with vehicle speed. As early as the 1920s engineers began to consider automobile shape in reducing aerodynamic drag at higher speeds. By the 1950s German and British automotive engineers were systematically analyzing the effects of automotive drag for the higher performance vehicles. By the late 1960s scientists also became aware of the significant increase in sound levels emitted by automobiles at high speed. These effects were understood to increase the intensity of sound levels for adjacent land uses at a non-linear rate. Soon highway engineers began to design roadways to consider the speed effects of aerodynamic drag produced sound levels, and automobile manufacturers considered the same factors in vehicle design.

Downforce

Downforce describes the downward pressure created by the aerodynamic characteristics of a car that allows it to travel faster through a corner by holding the car to the track or road surface. Some elements to increase vehicle downforce will also increase drag. It is very important to produce a good downward aerodynamic force because it affects the car's speed and traction.

Chapter 6

Automobile Drag Coefficient



Tatra T77 maquette by Paul Jaray, 1933

The **drag coefficient** is a common metric in automotive design pertaining to aerodynamic effects. As aerodynamic drag increases as the square of speed, a low value is preferable to a high one. With about 60% of the power required to cruise at

highway speeds being used to overcome aerodynamic effects minimizing drag translates directly into improved fuel efficiency.

For the same reason aerodynamics are of increasing concern to truck designers, where greater surface area presents substantial potential savings in fuel costs.

Reducing drag

Reducing drag is also a factor in sports car design, where fuel efficiency is less of a factor, but where low drag helps a car achieve a high top speed. However, there are other important aspects of aerodynamics that affect cars designed for high speed, including racing cars. Notably, it is important to minimize lift, hence increasing downforce, to avoid the car becoming airborne. Increasing the downforce pushes the car down onto the race track—allowing higher cornering speed. It is also important to maximize aerodynamic stability: some racing cars have tested well at particular "attack angles", yet performed catastrophically, i.e. flipping over, when hitting a bump or experiencing turbulence from other vehicles (most notably the Mercedes-Benz CLR). For best cornering and racing performance, as required in Formula One cars, downforce and stability are crucial and these cars must attempt to maximize downforce and maintain stability while attempting to minimize the overall C_d value.

Typical drag coefficients

The average modern automobile achieves a drag coefficient of between 0.30 and 0.35. SUVs, with their typically boxy shapes and larger frontal area, typically achieve a C_d of 0.35–0.45. A very gently inclined windshield gives a lower drag coefficient but has safety disadvantages, including reduced driver visibility. Certain cars can achieve figures of 0.25–0.30, although sometimes designers deliberately increase drag to reduce lift.

Some examples of C_d follow. Figures given are generally for the basic model. Some "high performance" models may actually have higher drag, due to wider tires and extra spoilers.

Production cars			Production cars (continued)		
C_d	Automobile	Year	C_d	Automobile	Year
0.7 to 1.1	typical values for a Formula One car (downforce settings change for each circuit)		0.315	Saturn SL1	1996-1999
0.74	Legends car		0.31	Audi A4 B5	1995
0.7	Caterham Seven		0.31	BMW 7-series	2009
0.6 +	a typical truck		0.31	Buick Park Avenue	1996
0.57	Hummer H2	2003	0.31	Cadillac CTS-V	2005
0.54	Mercedes Benz G-Class		0.31	Cadillac CTS	2004
0.51	Citroën 2CV	1948	0.31	Citroën AX	1986
0.48	Volkswagen Beetle (original design)	1938	0.31	Citroën GS	1970
0.48	Rover Mini	1998	0.31	Eagle Vision	1995
0.48	Volkswagen Cabriolet (Rabbit Convertible)	1979–1993	0.31	FIAT Coupé	1995
0.47	Lancia Aprilia	1937	0.31	Ford Falcon	1995
0.46	Ford Mustang (coupe)	1979	0.31	Ford Thunderbird	1989-1997
0.45	Range Rover Classic	1990	0.304	Ford Probe	1988-1992
0.45	Dodge Viper RT/10	1996	0.31	Holden Commodore	1998
0.44	Ford Mustang (fastback)	1979	0.31	Honda Civic (Sedan)	2006
0.44	Peugeot 305	1978	0.31	Honda Civic (Hatchback)	1992-1995
0.44	Peugeot 504	1968	0.31	Infiniti G37 (Coupe)	2008-2011
0.44	Toyota Truck	1990	0.31	Kia Rio (Sedan)	2001
0.43	TVR 3000S	1978-79	0.310	Lamborghini Diablo	1990
0.425	Duple 425 coach (named for its low C_d by coach standards)	1985	0.31	Lexus LFA (wing retracted)	2010
0.42	Lamborghini Countach	1974	0.31	Mazda RX-7 FC3S	1986
0.42	Triumph Spitfire Mk IV	1971	0.31	Mazda RX-7 FD R1(R2)	1993
0.42	Plymouth Duster	1994	0.31	Mazda RX-8	2004
0.41	Smart Roadster	2003	0.31	Mazda MX-6	1992–1997
0.41	Volvo 740 (sedan)	1982	0.31	Nissan Tiida / Versa	2004
0.405	Subaru Forester	1997-2002	0.31	Peugeot 307	2001
0.40	Ford Escape Hybrid	2005	0.31	Porsche 997 Turbo/GT3	2006
0.40	Nissan Skyline GT-R R32	1989	0.31	Renault 25	1984
0.40	Chevrolet Astro	1995-2005			
0.39	Ford Aerostar	1995			
0.39	Honda Odyssey	1994-98			

0.39	Chevrolet Tahoe	2006	0.31	Saab Sonett III	1970
0.39	Dodge Durango	2004	0.31	Saturn SC2	2001
0.39	Ford Escort 5 Door	1981-1984	0.31	Scion xA	2004
0.39	Triumph Spitfire	1964	0.31	Toyota Avalon	1995–2000
0.385	Nissan 280ZX	1978	0.31	Toyota Corolla	1998-2002
0.38	Smart Roadster Coupé	2003	0.32	Toyota Paseo	1995-1999
0.38	Smart ForTwo	1998	0.31	Toyota RAV4	2006
0.38	Lexus GX	2003		Toyota Supra	
0.38	Mazda Miata	1989	0.31	(N/A; without factory wing)	1993
0.38	Subaru Forester	2009	0.31	Volkswagen GTI Mk IV	1997
0.38	VW NewBeetle without wing or spoiler	0.39 2003	0.30	Audi 100	1983
0.374	Ford Capri Mk III	1978	0.30	Alfa Romeo 164 Sedan	1988
0.372	Ferrari F50	1996	0.30	Ford Taurus	1996-1999
0.37	BMW Z3 M coupe	1999	0.30	Honda Accord Sedan	2003, 2005–2007
0.37	Jaguar XJ (X300/X308)		0.30	Honda NSX	2002
0.37	Renault Twingo		0.30	Honda CRX DX/Si	1988
0.37	Volkswagen Tiguan	2008	0.30	Honda Odyssey	2005
0.36	Alfa Romeo 33	1983	0.30	Hyundai Sonata	2006
0.36	Cadillac Escalade hybrid	2008	0.30	Koenigsegg CCX	2006
0.36	Cadillac Fleetwood	1996	0.30	Mitsubishi Eclipse	2000
0.36	Volkswagen Jetta	1985-1992	0.30	Nissan 180SX	1989
0.36	Citroën CX (named after the term for C _d)	1974	0.30	Nissan 300ZX	1983
0.36	Citroën DS	1955		Nissan 350Z Coupe Base and Enthusiast models	2003–2008
0.36	Chrysler Sebring	1996	0.30	Nissan 370Z Coupe (0.29 with sport package)	2009
0.36	Ferrari Testarossa	1986	0.30	Renault 19 16V	1991
0.36	Ford Escort	1997-2002	0.30	Saab 92	1947
0.36	Ford Mustang	1999	0.30	Toyota Sienna	2003–2009
0.36	Honda Civic	2001–2005	0.30	Toyota Corolla	2003-2008
0.36	Opel GT	1969	0.295	Ford Falcon	1998
0.36	Subaru Impreza WRX	2010			
0.36	Saturn SW	1996-2001			
0.36	Toyota Celica Convertible	1994-1999			
0.355	NSU Ro 80	1967			

0.35	Aston Martin Vanquish	2004	0.291	Toyota Avalon	2005
0.35	BMW Z4 M coupe	2006	0.29	Alfa Romeo 155	1992
0.35	BMW M3 Convertible	2005		BMW 1-Series	
0.35	Dodge Viper GTS	1996	0.29	(116i Sportshatch)	2008
0.35	Honda Del Sol	1992–1997		Pontiac Firebird Trans Am	
0.35	Jaguar XKR	2005	0.29	(with optional W62 Aero Package and N89 Turbo Cast rims)	1984
0.35	Lexus GX	2010		BMW 8-Series	1989
0.35	Lexus RX	2003–2009	0.29	Chevrolet Corvette	2005
0.35	MINI Cooper	2008	0.29	Chevrolet Corvette C5 Z06	2002
0.35	Nissan Cube	2009	0.29	Daewoo Espero	1990
0.35	Renault Clio (Mk 2)	2002	0.29	Dodge Charger Daytona	1969
0.35	SSC Ultimate Aero	2007–present	0.29	Eagle Talon	1990s
0.35	Tesla Roadster	2008	0.29	Ford Escape	2010
0.35	Toyota MR-2	1998	0.29	Ford Focus C-Max	2003
0.35	Toyota Sequoia	2007	0.29	Honda Accord Hybrid	2005, 2007
0.35	Toyota Previa	1991–1997	0.29	Honda Accord Coupe	2003, 2005–2007
0.35	Volvo 940 (sedan)	1990	0.29	Honda CRX HF	1988
0.348	Toyota Celica Supra (Mk 2)	1982	0.29	Infiniti G35 Sedan	2008
0.342	Toyota Celica (Liftback Model)	1982	0.29	Lancia Dedra	1990
0.34	Subaru Impreza WRX (4 Door)	2009	0.29	Lexus LS 400	1990
0.34	Aston Martin DB9	2004	0.29	Lotus Elite	1958
0.34	Chevrolet Caprice	1994	0.29	Lotus Europa	1966
0.34	Chevrolet Tahoe hybrid	2008	0.29	Mazda Millenia	1995
0.34	Chevrolet C6 Corvette Z06	2005–present	0.29	Mazda RX-7 FC3S Aero Package	1986
0.34	Ferrari F40	1987	0.29	Mazda 3	2010
0.34	Ferrari 360 Modena	1999	0.29	Mazda RX-7 FD	1993
0.34	Ferrari F430 F1	2004	0.29	Mercedes-Benz SL (Roof Up)	2001
0.34	Ford Sierra	1982	0.29	Mercedes-Benz	2001
0.34	Ford Puma	1997			
0.34	Geo Metro (Hatchback)	1995–1997	0.29	Mercedes-Benz	2001
0.34	Honda Prelude	1988			
0.34	Mercedes-Benz SL (Roof Down)	2001			
0.34	Nissan Altima	1993–1997			
0.34	Peugeot 106	1991			

0.34	Saturn SL2	1991-1995	W203 C-Class Coupe	
0.34	Subaru Legacy Wagon	1993-1999	Nissan 350Z Coupe Track and Grand Touring	2007–2008
0.34	Toyota Supra (with factory 3 piece turbo wing)	1989–1990	Nissan Versa	2007–2008
0.34	Toyota Corolla (Wagon)	1993-1997	Peugeot 308	2007
0.338	Chevrolet Camaro	1995	Peugeot 407	2004
0.33	Audi A3	2006	Peugeot 607	1999
0.33	Acura Integra	1993-2001	Porsche Boxster	2005
0.33	Citroën SM	1970	Subaru XT	1985
0.33	Honda Civic Hatchback	1988-1991	Subaru SVX	1992
0.33	Dodge Charger	2006	Toyota Echo	2000–2005
0.33	Ford Crown Victoria	1992	Toyota Yaris	2007
0.33	Ford Fusion	2010	Toyota Camry]	1996–2001
0.33	Ford Escort ZX2	1998-2003	Toyota Prius	2001
0.33	Honda Accord Sedan	2002	Volvo C70	2000
0.33	Lamborghini Murcielago	2001	Chrysler Concorde	1998–2001
0.33	Lexus RX	2010	Chevrolet Corvette C6	2006
0.33	Mazda RX-7 FC3C	1987	Volkswagen Passat CC	2008
0.33	Nissan 200SX Coupe	1995-1998	Audi A2 1.4 TDI	2000
0.33	Peugeot 206	1998	Citroën XM	1989
0.33	Peugeot 309	1986	Citroën C4	2004
0.33	Renault Modus	2004	Lexus IS	2006–present
0.33	Subaru Impreza WRX STi	2004	Lexus LS400	1998
0.33	Saturn SL2	1999	Mitsubishi Diamante	1995
0.33	Toyota Corolla	1993-1997	Porsche 997 Carrera	
0.33	Toyota Supra (without wing)	1989–1990	(with optional automatic spoiler, PDK transmission 0.30)	2004
0.329	Chevrolet Corsica	1989-2006	Renault 25 TS	1984
0.324	Cobalt SS Supercharged	2005	Honda Civic Hybrid	2003–2005
0.321	Toyota Matrix	2003-2008	Rumpler-Tropfenwagen	1921
0.32	Volkswagen Golf MK3	1991	Saab 9-3	2003
0.32	AMC Pacer	1975–		

		1980	0.28	Toyota Camry /	2001
0.32	Ferrari California	2008		Lexus ES	
0.32	Buick Riviera	1995	0.28	Opel Astra	2003
0.32	BMW M3 Coupe	2005		Coupe Turbo	
0.32	Dodge Avenger	1995	0.28	Hyundai Elantra	2011
0.32	Ford Taurus	1992-	0.28	Opel Omega	1986
		1995		sedan	
0.32	Geo Metro (Sedan)	1995-	0.27	Nissan GTR	2008
		1997	0.27	Mazda Mazda6	2009
0.32	Honda Accord (Coupe)	2002	0.27	Audi A2 1.6 FSI	2003
0.32	Honda NSX	1990	0.27	Honda Civic	2006-
		1992-		Hybrid	
0.32	Honda Civic (Coupe)	1995	0.27	Hyundai Genesis	2009
0.32	Honda Civic (Hatchback DX)	1996-		Infiniti G35	
		2000	0.27	Coupe	2003–2007
0.32	Honda Civic (Sedan EX)	1996-		(0.26 with "aero	
		2000		package")	
0.32	Mazdaspeed3	2007	0.27	Lexus GS	2005
0.32	McLaren F1	1992	0.27	Mazda6 (sedan	2008
				and hatchback)	
0.32	Mercedes-Benz 190E 2.5-16/2.3-			Mercedes-Benz	
	16		0.27	W203 C-Class	2001
0.32	Nissan Altima	1998-		Sedan	
		2001	0.27	Nissan GT-R	2007-2010
0.32	Nissan 240SX Coupe	1995-	0.27	Toyota Camry	2007
		1998		Hybrid	
0.32	Nissan 300ZX	1989	0.27	Tucker Torpedo	1948
0.32	Nissan Maxima	1997		Volkswagen	
0.32	Porsche 997 GT2	2008–	0.27	Passat B5	1997
		present		(sedan)	
0.32	Peugeot 406	1995		Mercedes-Benz	
0.32	Peugeot 806	1994	0.27	S Class	2000–2005
0.32	Scion xB	2008		(0.268 with Sport	
				Package)	
0.32	Suzuki Swift	1991	0.27	Opel Insignia	2008–
0.32	Toyota Celica	1994		present	
0.32	Toyota Celica	2000-	0.26	Opel Insignia -	2009–
		2005		EcoFlex	present
0.32	Toyota Supra (N/A with wing	1993	0.26	BMW E90	2009
	and turbo models)			(0.26-0.30)	
0.32	Toyota Supra (with factory turbo	1987–	0.26	Chevrolet Volt	2010
	wing)	1988	0.26	Hotchkiss	1951
		1995-		Gregoire	
0.32	Toyota Tercel Sedan	2000	0.26	Lexus LS 430	2001–2006

0.32	Volkswagen GTI Mk V	2006	(0.25 with air suspension)
0.26	Lexus LS 460	2006	
0.26	Mercedes-Benz W221 S-Class	2006	
0.26	Mercedes-Benz W211 E-Class	2002-09	
0.26	Nissan GT-R	2010-present	
0.26	Opel Calibra (8 valve version)	1989	
0.26	Toyota Prius	2004–2009	
0.25	Audi A2 1.2 TDI	2001	
0.25	Honda Insight	1999, 2003, 2005	
0.25	Toyota Prius	2010	
	Mercedes E 220 CDI Blue Efficiency		
0.24	European version only, other E-Class Coupe 0.28 (0.25 sedan)	2009	
		1935	
0.212	Tatra T77A		
0.195	General Motors EV1	1996	

Concept/experimental cars

C_d	Automobile	Year
0.39	Porsche 918 Concept	2010
0.27	Avion	1986
0.26	Alfa Romeo Disco Volante	1952
0.25	Dymaxion Car	1933
0.25	SmILE (an experimental car)	1996
0.22	Citroën ECO 2000 Concept	1981
0.22	BMW Vision EfficientDynamics Concept	2009

		2006
0.20	Loremo Concept	20XX (Planned production)
0.20	Opel Eco Speedster Concept	2003
0.19	Alfa Romeo B.A.T. 7 Concept	1954
0.19	Dodge Intrepid ESX Concept	1995
0.19	Mercedes-Benz Bionic Concept(based on the boxfish)	2005
0.186	Schlör's Göttinger Ei	1939
0.186	Volkswagen XL1	2011
0.168	Daihatsu UFE-III Concept	2005
0.16	General Motors Precept Concept (5 seats)	2000
0.16	Edison2 Very Light Car, Automotive X Prize winner	2010
		2002
0.159	Volkswagen 1-litre car Concept	2013 (Planned production)
0.157	Li-ion Motors Wave II, Automotive X Prize winner	2010
0.15	Aptera 2 Series 2e	2011 (Planned production)
0.147	JCB Dieselmax land speed record holder	2006
0.146	Urbee Production vehicle	2010
0.14	Fiat Turbina Concept	1954
0.137	Ford Probe V Concept	1985
0.125	Sunraycer, solar race car	1987
0.12	Reflex 1000, solar cycle	1996
	Summers Brothers	
0.117	Goldenrod Bonneville race car	1965
0.08	Fortis Saxonia (Shell Eco-marathon) Concept	2007
0.075	PAC-Car II (Shell Eco-marathon) Concept	2005
0.07	Nuna, World Solar Challenge winner	2001–2007

Drag area

While designers pay attention to the overall shape of the automobile, they also bear in mind that reducing the frontal area of the shape helps reduce the drag. The combination of drag coefficient and area - drag area - is represented as C_dA (or C_xA), a multiplication of the C_d value by the area.

The term *drag area* derives from aerodynamics, where it is the product of some reference area (such as cross-sectional area, total surface area, or similar) and the drag coefficient. In 2003, *Car and Driver* magazine adopted this metric as a more intuitive way to compare the aerodynamic efficiency of various automobiles.

Average full-size passenger cars have a drag area of roughly 8.50 sq ft (0.790 m²). Reported drag areas range from the 1999 Honda Insight at 5.10 sq ft (0.474 m²) to the 2003 Hummer H2 at 26.3 sq ft (2.44 m²). The drag area of a bicycle is also in the range of 6.5–7.5 sq ft (0.60–0.70 m²).

Automobile examples of C_dA

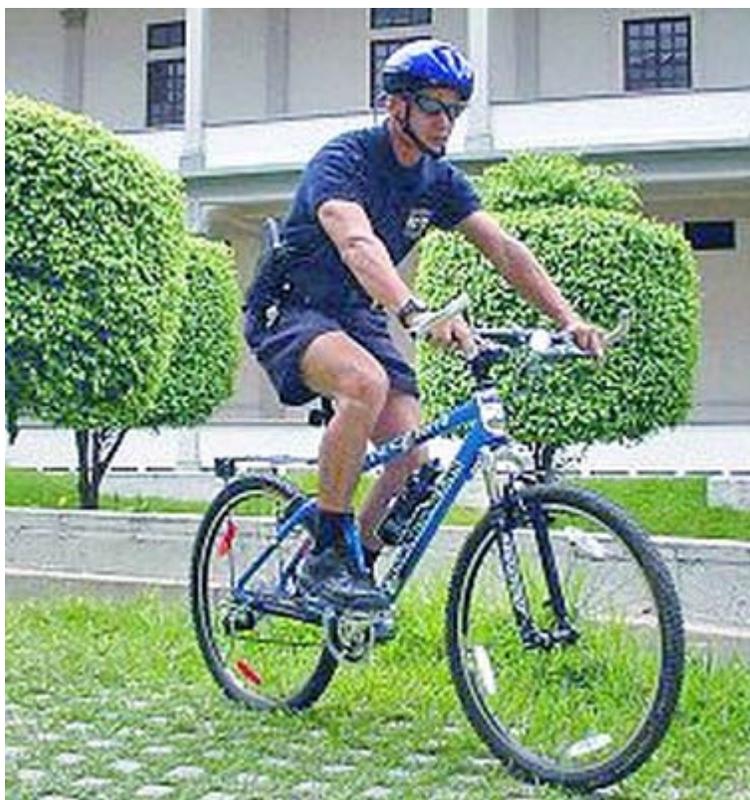
C_dA	Automobile model
2.50 sq ft (0.232 m ²)	1986 Twike
2.69 sq ft (0.250 m ²)	2009 Loremo
3.00 sq ft (0.279 m ²)	2011 Volkswagen XL1
3.95 sq ft (0.367 m ²)	1996 GM EV1
5.10 sq ft (0.474 m ²)	1999 Honda Insight
5.40 sq ft (0.502 m ²)	1989 Opel Calibra
5.71 sq ft (0.530 m ²)	1990 Honda CR-X Si
5.74 sq ft (0.533 m ²)	2002 Acura NSX
5.76 sq ft (0.535 m ²)	1968 Toyota 2000GT
5.80 sq ft (0.539 m ²)	1986 Toyota MR2
5.81 sq ft (0.540 m ²)	1989 Mitsubishi Eclipse GSX
5.86 sq ft (0.544 m ²)	2001 Audi A2 1.2 TDI 3L
5.88 sq ft (0.546 m ²)	1990 Nissan 240SX hatchback / 200SX / 180SX
5.92 sq ft (0.550 m ²)	1994 Porsche 911 Speedster
5.95 sq ft (0.553 m ²)	1990 Mazda RX7
6.00 sq ft (0.557 m ²)	1992 Subaru SVX
6.00 sq ft (0.557 m ²)	1970 Lamborghini Miura
6.08 sq ft (0.565 m ²)	2008 Nissan GTR
6.13 sq ft (0.569 m ²)	1991 Acura NSX
6.17 sq ft (0.573 m ²)	1995 Lamborghini Diablo
6.24 sq ft (0.580 m ²)	2004 Toyota Prius
6.27 sq ft (0.583 m ²)	1986 Porsche 911 Carrera

6.27 sq ft (0.583 m²) 1992 Chevrolet Corvette
6.35 sq ft (0.590 m²) 1999 Lotus Elise
6.37 sq ft (0.592 m²) 2000 Vauxhall VX220 N/A
6.40 sq ft (0.595 m²) 1990 Lotus Esprit
6.41 sq ft (0.596 m²) 2003 Smart Roadster Coupé
6.54 sq ft (0.608 m²) 1991 Saturn Sports Coupe
6.57 sq ft (0.610 m²) 1985 Chevrolet Corvette
6.63 sq ft (0.616 m²) 2001 Audi A2
6.63 sq ft (0.616 m²) 1989 Ford Thunderbird
6.66 sq ft (0.619 m²) 1996 Citroën Saxo
6.77 sq ft (0.629 m²) 1995 BMW M3
6.79 sq ft (0.631 m²) 1993 Toyota Corolla DX
6.80 sq ft (0.632 m²) 2007 BMW 335i Coupe
6.81 sq ft (0.633 m²) 1991 Subaru Legacy
6.90 sq ft (0.641 m²) 1993 Saturn Wagon
6.93 sq ft (0.644 m²) 1982 Delorean DMC-12
6.94 sq ft (0.645 m²) 2003 Smart Roadster
6.96 sq ft (0.647 m²) 1988 Porsche 944 S
6.96 sq ft (0.647 m²) 1995 Chevrolet Lumina LS
7.02 sq ft (0.652 m²) 1992 BMW 325I
7.04 sq ft (0.654 m²) 1991 Honda Civic EX
7.06 sq ft (0.656 m²) 2004 Vauxhall VX220 Turbo
7.10 sq ft (0.660 m²) 1995 Saab 900
7.14 sq ft (0.663 m²) 1995 Subaru Legacy L
7.20 sq ft (0.669 m²) 1995 Nissan Maxima GLE
7.34 sq ft (0.682 m²) 2001 Honda Civic
7.39 sq ft (0.687 m²) 1994 Honda Accord EX
7.48 sq ft (0.695 m²) 1993 Chevrolet Camaro Z28
7.57 sq ft (0.703 m²) 1992 Toyota Camry
7.69 sq ft (0.714 m²) 1994 Chrysler LHS
7.72 sq ft (0.717 m²) 1993 Subaru Impreza
8.02 sq ft (0.745 m²) 2005 Bugatti Veyron
8.70 sq ft (0.808 m²) 1990 Volvo 740 Turbo
8.70 sq ft (0.808 m²) 1992 Ford Crown Victoria
8.71 sq ft (0.809 m²) 1991 Buick LeSabre Limited
9.54 sq ft (0.886 m²) 1992 Chevrolet Caprice Wagon
10.7 sq ft (0.99 m²) 1992 Chevrolet Blazer
11.6 sq ft (1.08 m²) 2005 Ford Escape Hybrid

- 11.7 sq ft (1.09 m²) 1993 Jeep Grand Cherokee
- 16.8 sq ft (1.56 m²) 2006 Hummer H3
- 17.4 sq ft (1.62 m²) 1995 Land Rover Discovery
- 26.5 sq ft (2.46 m²) 2003 Hummer H2

Selected photographs







0.57 - 2003 Hummer H2





















Chapter 7

Vehicle Dynamics

Vehicle dynamics refers to the dynamics of vehicles, here assumed to be ground vehicles. Vehicle dynamics is a part of engineering primarily based on classical mechanics but it may also involve chemistry, solid state physics, electrical engineering, communications, psychology, control theory, etc.

.Components

Components, attributes or aspects of vehicle dynamics include:

- Electronic Stability Control (ESC)
- Steering
- Suspension
- Traction control system (TCS)

Aerodynamic specific

Some attributes or aspects of vehicle dynamics are purely aerodynamic. These include:

- Automobile drag coefficient
- Automotive aerodynamics
- Center of pressure
- Downforce
- Ground effect in cars

Geometry specific

Some attributes or aspects of vehicle dynamics are purely geometric. These include:

- Ackermann steering geometry
- Axle track
- Camber angle
- Caster angle
- Ride height
- Roll center
- Toe
- Wheelbase

Mass specific

Some attributes or aspects of vehicle dynamics are purely due to mass and its distribution. These include:

- Center of mass
- Moment of inertia
- Sprung mass
- Unsprung mass
- Weight distribution

Motion specific

Some attributes or aspects of vehicle dynamics are purely dynamic. These include:

- Body flex
- Bump Steer
- Directional stability
- Critical speed
- Load transfer
- Noise, vibration, and harshness
- Oversteer
- Ride quality
- Speed wobble
- Understeer
- Weight transfer

Tire specific

Some attributes or aspects of vehicle dynamics can be attributed directly to the tires. These include:

- Camber thrust
- Circle of forces
- Contact patch
- Cornering force
- Ground pressure

- Pacejka's Magic Formula
- Pneumatic trail
- Relaxation length
- Rolling resistance
- Self aligning torque
- Slip angle
- Slip (vehicle dynamics)
- Steering ratio
- Tire load sensitivity

Driving techniques

Driving techniques which relate to, or improve the stability of vehicle dynamics include:

- Cadence braking
- Threshold braking
- Double declutching
- Drifting (motorsport)
- Handbrake turn
- Heel-and-Toe
- Left-foot braking
- Opposite lock
- Scandinavian flick

Analysis and simulation

The dynamic behavior of vehicles can be analysed in several different ways. This can be as straightforward as a simple spring mass system, through a 3 degree of freedom (DoF) bicycle model, to a large degree of complexity using a multibody system simulation package such as MSC ADAMS or Modelica. As computers have gotten faster, and software user interfaces have improved, commercial packages such as CarSim have become widely used in industry for rapidly evaluating hundreds of test conditions much faster than real time. Vehicle models are often simulated with advanced controller designs provided as software in the loop (SIL) with controller design software such as Simulink, or with physical hardware in the loop (HIL).

Vehicle motions are largely due to the shear forces generated between the tires and road, and therefore the tire model is an essential part of the math model. The tire model must produce realistic shear forces during braking, acceleration, cornering, and combinations, on a range of surface conditions. Many models are in use. Most are semi-empirical, such as the Pacejka Magic Formula model.

Racing car games or simulators are also a form of vehicle dynamics simulation. In early versions many simplifications were necessary in order to get real-time performance with reasonable graphics. However, improvements in computer speed

have combined with interest in realistic physics, leading to driving simulators that are used for vehicle engineering using detailed models such as CarSim.

It is important that the models should agree with real world test results, hence many of the following tests are correlated against results from instrumented test vehicles.

Techniques include:

- Linear range constant radius understeer
- Fishhook
- Frequency response
- Lane change
- Moose test
- Sinusoidal steering
- Swept path analysis

Chapter 8

Automotive Industry

The **automotive industry** designs, develops, manufactures, markets, and sells motor vehicles, and is one of the world's most important economic sectors by revenue.

The term *automotive industry* usually does not include industries dedicated to automobiles after delivery to the customer, such as repair shops and motor fuel filling stations.

Consumption trends

About 250 million vehicles are in use in the United States. Around the world, there were about 806 million cars and light trucks on the road in 2007, consuming over 260 billion gallons of gasoline and diesel fuel yearly. In the opinion of some, urban transport systems based around the car have proved unsustainable, consuming excessive energy, affecting the health of populations, and delivering a declining level of service despite increasing investments. Many of these negative impacts fall disproportionately on those social groups who are also least likely to own and drive cars. The sustainable transport movement focuses on solutions to these problems.

The Detroit branch of Boston Consulting Group predicts that, by 2014, one-third of world demand will be in the four BRIC markets (Brazil, Russia, India and China). Other potentially powerful automotive markets are Iran and Indonesia.

History

The first practical automobile with a petrol engine was built by Karl Benz in 1885 in Mannheim, Germany. Benz was granted a patent for his automobile on 29 January 1886, and began the first production of chevy automobiles in 1888, after Bertha Benz,

his wife, had proved with the first long-distance trip in August 1888 - from Mannheim to Pforzheim and back - that the horseless coach was absolutely suitable for daily use. Since 2008 a Bertha Benz Memorial Route commemorates this event.

Soon after, Gottlieb Daimler and Wilhelm Maybach in Stuttgart in 1889 designed a vehicle from scratch to be an automobile, rather than a horse-drawn carriage fitted with an engine. They also are usually credited as inventors of the first motorcycle, the Daimler *Reitwagen*, in 1885, but Italy's Enrico Bernardi, of the University of Padua, in 1882, patented a 0.024 horsepower (17.9 W) 122 cc (7.4 cu in) one-cylinder petrol motor, fitting it into his son's tricycle, making it at least a candidate for the first automobile, and first motorcycle;^{p.26} Bernardi enlarged the tricycle in 1892 to carry two adults.^{p.26}

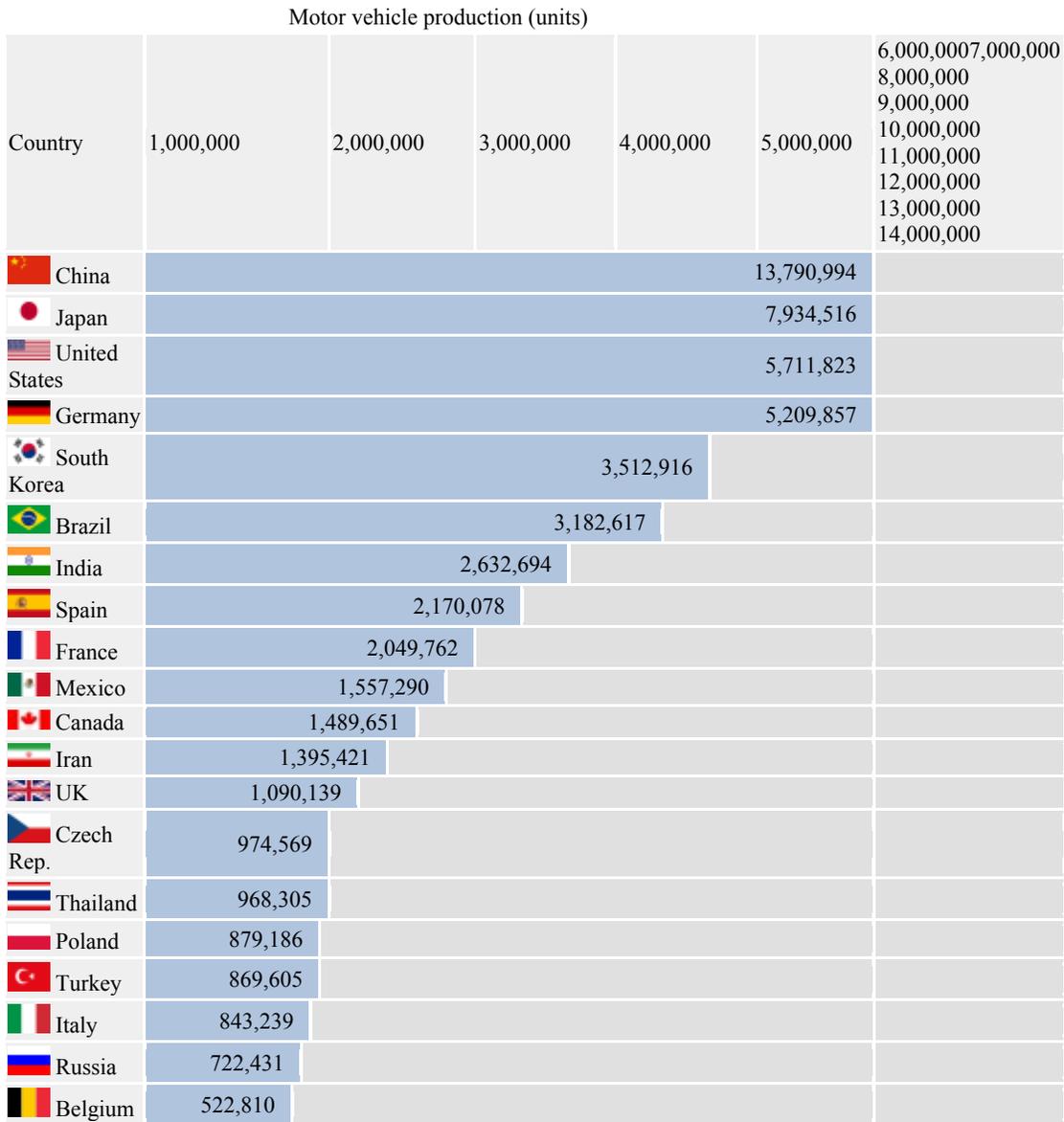
By year

Global Production of Motorvehicles

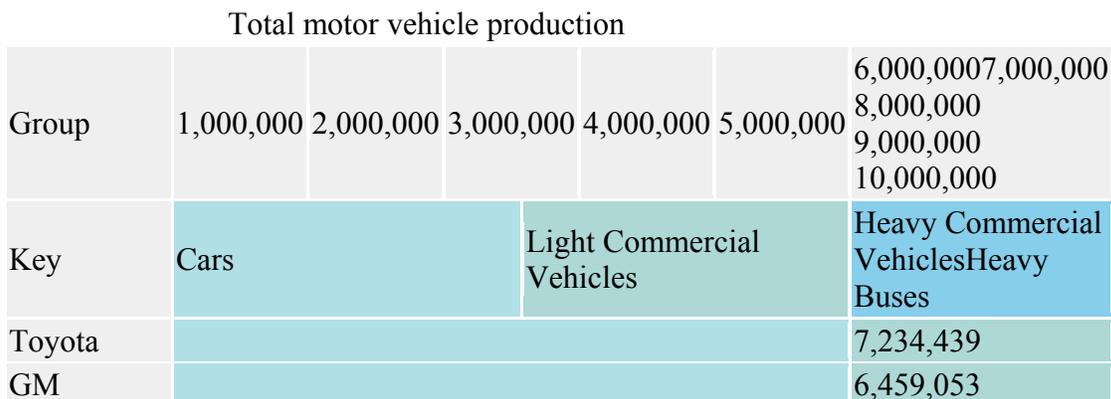
(cars and commercial vehicles)

Year	Production	Change	Source
1997	52,987,000		
1998	57,987,000	-2.70%	
1999	56,258,892	2.98%	
2000	58,374,162	3.80%	
2001	56,304,925	-3.50%	
2002	58,994,318	4.80%	
2003	60,663,225	2.80%	
2004	64,496,220	6.30%	
2005	66,482,439	3.10%	
2006	69,222,975	4.10%	
2007	73,266,061	5.80%	
2008	70,520,493	-3.70%	
2009	60,986,985	-13.50%	

By country



By manufacturer



Volkswagen	6,054,829
Ford	4,685,394
Hyundai Kia	4,645,776
PSA	3,042,311
Honda	3,012,637
Nissan	2,744,562
Fiat	2,460,222
Suzuki	2,387,537
Renault	2,296,009
Daimler AG	1,447,953
Chana Automobile	1,425,777
BMW	1,258,417
Mazda	984,520
Chrysler	959,070
Mitsubishi	802,463
Beijing Automotive	684,534
Tata	672,045
Dongfeng Motor	663,262
FAW	650,275
Chery	508,567
Fuji	491,352
BYD	427,732
SAIC	347,598
Jianghuai	336,979
Geely	330,275
Isuzu	316,335
Brilliance	314,189
AvtoVAZ	294,737
Great Wall	226,560
Mahindra	223,065
Shangdong Kaima	169,023
Proton	152,965
China National	120,930

Volvo	105,873		
Chongqing Lifan	104,434		
Fujian Motor Industry Group	103,171		
Kuozui	93,303		
Shannxi Auto	79,026		
Porsche	75,637		
Ziyang Nanjun	72,470		
GAZ	69,591		
Navistar	65,364		
Guangzhou Auto	62,990		
Paccar	58,918		
Chenzhou Ji'ao	51,008		
Qingling Motor	50,120		
Hebei Zhongxing	48,173		
Ashok Leyland	47,694		
Key	Cars	Light Commercial Vehicles	Heavy Commercial Vehicles Heavy Buses
Total: 60,499,159	Cars: 51,075,480	LCV: 7,817,520	HCV: 1,305,755 Heavy Bus: 300,404

Company relationships

It is common for automobile manufacturers to hold stakes in other automobile manufacturers. These ownerships can be explored under the detail for the individual companies.

Notable current relationships include:

- Daimler AG holds a 20% stake in Eicher Motors, a 10.0% stake in KAMAZ, a 10% stake in Tesla Motors, a 6.75% stake in Tata Motors and a 3.1% in the Renault-Nissan Motors alliance. They are in the process of selling back their 40% stake in McLaren Group. This process will be finalized in 2011.
- Dongfeng Motor Corporation is involved in joint ventures with several companies around the world, including: Honda (Japan), Hyundai (South Korea), Nissan (Japan), Nissan Diesel (Sweden), and PSA Peugeot Citroen (France).
- Fiat holds a 90% stake in Ferrari and a 25% stake in Chrysler, that can be increased to 51%; with the option of increasing its stake further.
- Ford Motor Company holds a 3% stake in Mazda and an 8.3% share in Aston Martin.
- Geely Automobile holds a 23% stake in Manganese Bronze Holdings.
- General Motors and Shanghai Automotive Industry Corporation (SAIC) have two joint ventures in Shanghai General Motors and SAIC-GM-Wuling Automobile.
- Hyundai Kia Automotive Group holds a 38.67% stake in Kia Motors, down from the 51% that it acquired in 1998.
- Renault Pars is a joint venture, 51 percent of which belongs to Renault of France. Forty-nine percent of Renault Pars' shares is jointly held by Iran's Industrial Development and Renovation Organization, IKCO and Saipa. The company was established in 2003.
- MAN SE holds a 17.01% voting stake in Scania.
- Porsche Automobil Holding SE has a 50.74% stake in Volkswagen Group. Due to liquidity problems, Volkswagen Group is now in the process of acquiring Porsche.
- Renault-Nissan Motors have an alliance involving two global companies linked by cross-shareholding, with Renault holding 44.3% of Nissan shares, and Nissan holding 15% of (non-voting) Renault shares. The alliance holds a 3.1% share in Daimler AG.
- Renault holds a 25% stake in AvtoVAZ and 20.5% of the voting stakes in Volvo Group.
- Toyota holds a 51% stake in Daihatsu, and 16.5% in Fuji Heavy Industries, parent company of Subaru.
- Volkswagen Group and FAW have a joint venture.
- Volkswagen Group and Shanghai Automotive Industry Corporation (SAIC) have a joint venture in Shanghai Volkswagen Automotive.
- Volkswagen Group holds a 37.73% stake in Scania (68.6% voting rights), and a 29% stake in MAN SE.
- Volkswagen Group has a 49.9% stake in Porsche AG. Volkswagen is in the process of acquiring Porsche, which will be completed in mid-2011.
- Volkswagen Group has a 19.9% stake in Suzuki, and Suzuki has a 5% stake in Volkswagen.

Top vehicle manufacturing groups (by volume)

The table below shows the world's largest motor vehicle manufacturing groups, along with the marques produced by each one. The table is ranked by 2009 *end of year* production figures from the International Organization of Motor Vehicle Manufacturers (OICA) for the parent group, and then alphabetically by marque. Joint ventures are not reflected in this table. Production figures of joint ventures are typically included in OICA rankings, which can become a source of controversy.

Marque	Country of origin	Ownership	Markets
1. Toyota Motor Corporation ( Japan)			
Daihatsu		Subsidiary	Global, except North America and Australia
Hino		Subsidiary	Asia Pacific, North America and South America
Lexus		Division	Global
Scion		Division	North America
Toyota		Division	Global
2. General Motors Company ( United States)			
Buick		Division	North America, Middle East, East Asia, except Japan
Cadillac		Division	Global, except South America, South Asia, South East Asia, Pacific
Chevrolet		Division	Global, except Australia, New Zealand, South Korea
GMC		Division	North America, Middle East
GM Daewoo		Subsidiary	South Korea, Vietnam
Holden		Subsidiary	Australia, New Zealand, Japan
Opel		Subsidiary	Europe (except United Kingdom), Middle East/Africa, Asia/Pacific except Japan, Korea and Vietnam
Vauxhall		Division	United Kingdom
3. Volkswagen Group AG ( Germany)			
Audi		Subsidiary	Global
Bentley		Subsidiary	Global
Bugatti		Subsidiary	Global
Lamborghini		Subsidiary	Global
Scania		Subsidiary	Global
SEAT		Subsidiary	Europe, South America, North Africa, Middle East
Škoda		Subsidiary	Global, except North America, Japan and

Volkswagen		Subsidiary	Global	South Africa
Volkswagen Commercial Vehicles		Subsidiary	Global	
4. Renault-Nissan ( France  Japan)				
Dacia		Subsidiary	Europe, Latin America, Africa, Asia, except Japan	
Renault (cars)		Division	Global, except North America, South Korea	
Renault Samsung		Subsidiary	South America, Asia, except Japan and China	
Infiniti		Division	Global, except Japan, South America and Africa	
Nissan		Division	Global	
5. Ford Motor Company ( United States)				
Ford		Division	Global	
Lincoln		Division	North America, Middle East, Japan, South Korea	
Troller		Subsidiary	South America and Africa	
6. Hyundai Motor Company ( South Korea)				
Hyundai		Division	Global	
Kia		Division	Global	
7. PSA Peugeot Citroën S.A. ( France)				
Citroën		Subsidiary	Global, except North America, South Asia	
Peugeot		Subsidiary	Global, except North America, South Asia	
8. Honda Motor Company ( Japan)				
Acura		Division	North America, East Asia, except Japan	
Honda		Division	Global	
9. Fiat S.p.A. ( Italy)				
Abarth		Subsidiary	Global, except North America	
Alfa Romeo		Subsidiary	Global	
Ferrari		Subsidiary	Global	
Fiat		Subsidiary	Global	
Fiat Professional		Subsidiary	Global, except North America and Japan	
Iveco		Subsidiary	Global, except North America	
Lancia		Subsidiary	Europe and Japan	
Maserati		Subsidiary	Global	

10. Suzuki Motor Corporation (Japan)

Maruti Suzuki		Subsidiary	India, Middle East, South America
Pak Suzuki Motors		Subsidiary	Pakistan
Suzuki		Division	Global

11. Daimler AG (Germany)

Freightliner		Subsidiary	North America, South Africa
Master		Subsidiary	Pakistan
Maybach		Division	Global
Mercedes-Benz		Division	Global
Mitsubishi Fuso		Subsidiary	Global
Orion		Subsidiary	North America
Setra		Subsidiary	Europe
Smart		Division	North America, Europe, Japan, South East Asia, South Africa
Thomas Built		Subsidiary	North America
Western Star		Subsidiary	North America

12. Chana Automobile Company, Ltd (People's Republic of China)

Chana		Division	China, South Africa
Hafei		Subsidiary	China

13. BMW AG (Germany)

BMW		Division	Global
MINI		Division	Global
Rolls-Royce		Subsidiary	Global

14. Mazda Motor Corporation (Japan)

Mazda		Division	Global
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15. Chrysler Group, LLC (United States)

Chrysler		Division	Global
Dodge		Division	Global
GEM		Division	North America
Jeep		Division	Global
Ram		Division	North America

16. Mitsubishi Motors Corporation (Japan)

Mitsubishi		Division	Global
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17. Beijing Automotive Industry Holding Corporation, Ltd (People's Republic of China)

BAW		Division	China
Foton		Subsidiary	China

18. Tata Motors, Ltd (India)

Hispano		Subsidiary	Europe
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Jaguar		Subsidiary	Global
Land Rover		Subsidiary	Global
Tata		Division	India, South Africa
Tata Daewoo		Subsidiary	South Korea

19. Dongfeng Motor Corporation (People's Republic of China)

Dongfeng		Division	China
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20. First Automotive Group Corporation (People's Republic of China)

Besturn		Division	China
Freewind		Subsidiary	China
Haima		Subsidiary	China
Hongqi		Division	China
Jiaxing		Subsidiary	China
Vita		Subsidiary	China
Xiali		Subsidiary	China

21. Chery Automobile Company, Ltd (People's Republic of China)

Chery		Division	China, Africa, South East Asia, Russia
Riich		Division	China
Rely		Division	China

22. Fuji Heavy Industries, Ltd (Japan)

Subaru		Division	Global
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23. BYD Auto (People's Republic of China)

BYD		Division	China, Russia
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24. Shanghai Automotive Industry Corporation (People's Republic of China)

MG		Subsidiary	United Kingdom, Chile, Argentina, China
SsangYong**		Subsidiary	Global
Roewe		Division	China
Soyat		Division	China
Yuejin		Division	China

25. Anhui Jianghuai Automobile Company, Ltd (People's Republic of China)

JAC		Division	China
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26. Geely Automobile (People's Republic of China)

Geely		Division	China, Russia, North Africa
Maple		Division	China
Volvo (Cars)		Subsidiary	Global

27. Isuzu Motors, Ltd (Japan)

Isuzu		Division	Global, except North America
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28. Brilliance China Automotive Holding, Ltd ( People's Republic of China)

Brilliance		Division	China, North Africa
Jinbei		Subsidiary	China

29. OAO AvtoVAZ ( Russia)

Lada		Division	Russia, Europe, North Africa
VAZ		Division	Russia, Europe

30. Great Wall Motor Company, Ltd ( People's Republic of China)

Great Wall		Division	China, South Africa, Russia, North Africa, Australia
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31. Mahindra & Mahindra, Ltd ( India)

Mahindra		Division	India, South East Asia, Europe, North Africa, North America
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32. Shandong Kaima ( China)

Kaima		Division	China
Jubao		Division	China
Aofeng		Division	China

33. Proton Holdings, Bhd ( Malaysia)

Proton		Division	Asia Pacific (except Japan and South Africa), United Kingdom, Middle East
Lotus		Subsidiary	Global

34. China National Heavy Duty Truck Company, Ltd ( People's Republic of China)

Sinotruk		Division	China
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35. AB Volvo ( Sweden)

Mack		Subsidiary	Global
Nissan Diesel		Subsidiary	Global
NovaBus		Subsidiary	North America
Prevost		Subsidiary	North America
Renault (trucks)		Subsidiary	Global, except Japan
Volvo (trucks)		Division	Global

36. Chongqing Lifan Automobile Company, Ltd ( People's Republic of China)

Lifan		Division	China
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37. Fujian Motor Industry Group Company ( People's Republic of China)

Soueast		Division	China
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38. Kuozui Motors, Ltd ( Taiwan)

Kuozui		Subsidiary	Taiwan
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39. Shaanxi Automobile Group Company, Ltd ( People's Republic of China)

China)			
Shaanxi		Division	China
40. Porsche ( Germany)			
Porsche		Subsidiary	Global
41. Ziyang Nanjun Automobile Co., Ltd. ( People's Republic of China)			
Nanjun		Division	China
42. GAZ Group ( Russia)			
GAZ		Subsidiary	Russia
KAvZ		Subsidiary	Russia
LiAZ		Subsidiary	Russia
UralAZ		Division	Russia
43. Navistar International Corporation ( United States)			
IC		Subsidiary	North America
International		Division	North America, South Asia
44. Guangzhou Automobile Group ( China)			
Changfeng		Division	China
45. Paccar, Inc ( United States)			
DAF		Subsidiary	Global, except North America
Kenworth		Division	North America
Leyland		Subsidiary	Europe
Peterbilt		Division	North America
46. Chenzhou Ji'ao ( China)			
Ji'ao		Division	China
47. Qingling Motors Company Ltd. ( China)			
Qingling		Division	China
48. Hebei ZX AUTO ( China)			
Zhongxing		Division	China
49. Ashok Leyland ( India)			
Ashok Leyland		Division	India

Notes

* Porsche Automobil Holding SE has a 50.7 percent share in the Volkswagen Group. However, Volkswagen Group will acquire Porsche AG, the automotive manufacturer under a new "Integrated Automotive Group". This merger/acquisition is expected to be fully completed in mid-2011.

** Shanghai Automotive Industry Corporation is in the process of selling SsangYong Motor Company to Mahindra & Mahindra.

Minor automotive manufacturers

There are many automobile manufacturers other than the major global companies. They are mostly regional or operating in niche markets.