

Analysis, Design and Application of Continuously Variable Transmission (CVT)

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ABSTRACT

Continuously Variable Transmission (CVT) offers a continuum of gear ratios between desired limits. This allows the engine to operate more time in the optimum range. In contrast, traditional automatic and manual transmissions have several fixed transmission ratios forcing the engine to operate outside the optimum range. The need for a transmission system and the working principle of CVT has been discussed in depth. An attempt has been made to understand the contribution of Hydraulic Actuators, which is an integral part of a CVT. Furthermore, the question of how and why a Torque Converter has effectively replaced a conventional clutch has been answered. The materials used, constructional aspects and stress analysis of the belt has been discussed in detail. A graphical comparison of fuel efficiency between a manual transmission and a CVT in different high end vehicles is included. Recent developments in clamping force control for the push belt Continuously Variable Transmission (CVT) have resulted in increased efficiency in combination with improved robustness. Current control strategies attempt to prevent macro slip between elements and pulleys at all times for maximum robustness.

Keywords - Belt Design, CVT, Hydraulic Actuators, Torque Converter, Transmission

I. INTRODUCTION

A Continuously Variable Transmission (CVT) has been around for more than a 100 years, but has only recently found its way into automotive applications. The overwhelming majority of transmissions in road going vehicles are either manual or conventional automatic in design. These transmissions use meshing gears that give discrete ratio steps between engine and the vehicle speed. However, alternative designs exist that can transmit power and simultaneously give a step less change of ratio; in other words a Continuously Variable Transmission. Continuously Variable Transmission is a type of automatic transmission that provides an uninterrupted range of speed ratios, unlike a normal transmission that provides only a few discrete ratios.

However, until recently it was reserved for industrial applications like running lathes or light duty drill presses. But with the introduction of improved materials, such as high density belts, advanced hydraulics and more recently, high speed sensors and microprocessors, the stage was set for CVT's rise in the automobile arena.

Many small tractors for home and garden use have simple rubber belt CVTs. For example, the John Deere Gator lines of small utility vehicles use a belt with a conical pulley system. They can deliver an abundance of power and can reach speeds of 10–15 mph (16–24 km/h), all without need for a clutch or shifting gears. Nearly all snowmobiles, old and new,

and motor scooters use CVTs, typically the rubber belt/variable pulley variety.

II. TRANSMISSION

The understanding of the meaning and function of a simple transmission is a pre-requisite to the CVT.

The transmission adapts the output of the internal combustion engine to the drive wheels. Such engines need to operate at a relatively high rotational speed, which is inappropriate for starting, stopping, and slower travel. The transmission reduces the higher engine speed to the slower wheel speed, increasing torque in the process.

The transmission will generally be connected to the crankshaft of the engine. The output of the transmission is transmitted via driveshaft to one or more differentials, which in turn, drive the wheels.

The need for a transmission in an automobile is a consequence of the characteristics of the internal combustion engine. Engines typically operate over a range of 600 to about 7000 revolutions per minute (though this varies, and is typically less for diesel engines), while the car's wheels rotate between 0 rpm and around 1800 rpm. Often the greatest torque is required when the vehicle is moving from rest or traveling slowly, while maximum power is needed at high speed. Therefore, a system that transforms the engine's output so that it can supply high torque at low speeds, but also operate at highway speeds with

the motor still operating within its limits, is required. Transmissions perform this transformation.

The structural aspects of the transmission, predominantly the casting, often contribute significantly to the structure of the power train and the vehicle as a whole. This is important when it comes to engineering for the lowest noise and vibration. The stiffness of the power train assembly itself is important in determining the magnitude and frequency of the vibrations at the source (the engine).

II.1 OPTIMUM RPM RANGE

An automobile engine runs at its best efficiency at a certain Revolutions Per Minute (RPM) range and it is the transmission's function to make sure that the power is delivered to the wheels while keeping the engine speed within this optimum range. The transmission accomplishes this through various gear combinations.

In addition to the various forward gears, a transmission also has a Neutral stance which disconnects the engine from the drive wheels, and the Reverse stance, which causes the drive wheels to turn in the opposite direction thereby reversing the direction of the car.

III. CONTINUOUSLY VARIABLE TRANSMISSION (CVT)

A Continuously Variable Transmission (CVT) is a transmission that can change steplessly through an infinite number of effective gear ratios between maximum and minimum values.

On the other hand, the conventional mechanical transmissions offer only a fixed set of gear ratios. The unique feature of a CVT allows the driving shaft to maintain a constant angular velocity over a range of output velocities. This property produces better fuel efficiency compared to other transmissions by allowing the engine to run at its most efficient revolutions per minute (RPM) for a range of automobile speeds.

Another possibility is that a CVT can be used to achieve the best automobile performance by permitting the engine to revolve at the RPM at which it produces the peak power. This is normally higher than the RPM that achieves peak efficiency.

The use of CVT makes the engine to go from an idle to a pre-programmed rpm immediately, so the engine input is constant and then varies the output speed for smooth, seamless acceleration. CVTs enable power application without any jerk.

The continuously variable transmission (CVT) has been around as long as the automobile. Engineers have always recognized its theoretical advantage over the multi ratio gearbox. A CVT enables the engine to run at its most fuel-efficient or most power-efficient speed while driving the vehicle at any speed desired.

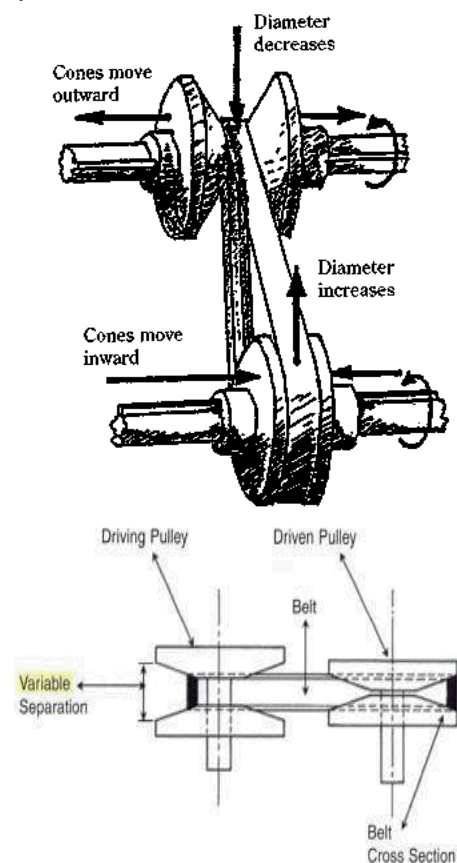
With a CVT, engine speed and vehicle speed are no longer connected by a series of discrete ratios. Instead, they can function independently across a wide and step less band according to engine characteristics and performance requirements. The advantages of this infinite ratio selectivity are enormous. Most obvious in the IC engine application is that the engine can be loaded into its most fuel-efficient region at cruising speeds, then allowed to accelerate into its region of greatest output when peak power is needed, regardless of vehicle speed. Practical problems have consistently plagued the design, but the CVT is now coming of age.

III.1. COMPONENTS OF A CVT

1. A high power/density belt.
2. A set of Cone pulleys.
3. Hydraulic Actuator.
4. Mechanical torque sensor.
5. Microprocessor.
6. Torque Converter or Multi-layered clutch (replacing conventional clutches).

IV. WORKING PRINCIPLE OF A CVT

A Continuously Variable Transmission operates by varying the working diameter of the two main pulleys in the transmission.



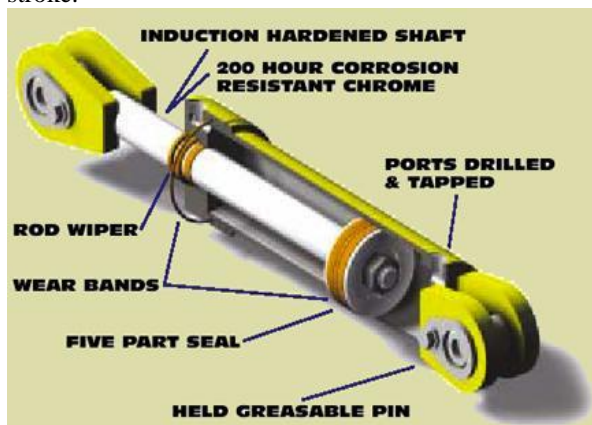
Fig(1): Working of CVT.

The pulleys have V-shaped grooves on which the connecting belt is mounted. One side of the pulley is fixed; the other side is moveable, operated by a hydraulic actuator. The hydraulic actuator can increase or decrease the amount of space between the two sides of the pulley. This makes the belt to ride lower or higher along the inner walls of the pulley, depending on driving conditions, thereby changing the gear ratio. This action is infinitely variable with no "steps" in between. Thus a CVT can maintain the engine in its optimum rpm range, in turn boosting the efficiency and gas Mileage.

As explained above the two pulley widths are adjusted by oil pressure in the hydraulic actuator which responds to position of the throttle, speed, and other conditions, which are sensed by microprocessors & other sensors.

IV.1. HYDRAULIC ACTUATORS

A **Hydraulic Actuator** (also called a linear hydraulic motor) is a mechanical device that is used to give a unidirectional force through a unidirectional stroke.



Fig(2): A Cut Away of a Hydraulic Actuator.

Hydraulic Actuators get their power from pressurized hydraulic fluid, which is typically oil. The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod moves back and forth. The barrel is closed on each end by the cylinder bottom (also called the cap end) and by the cylinder head where the piston rod comes out of the cylinder. The piston has sliding rings and seals. The piston divides the inside of the cylinder in two chambers - the bottom chamber (cap end) and the piston rod side chamber (rod end). The hydraulic pressure acts on the piston to do linear work and motion.

The piston rod also has mounting attachments to connect the cylinder to the object or machine component that it is pushing/pulling.

A hydraulic cylinder is the actuator or "motor" side of this system. The "generator" side of the hydraulic system is the hydraulic pump which brings

in a fixed or regulated flow of oil to the bottom side (i.e. bottom chamber) of the hydraulic cylinder, to move the piston rod upwards. The piston pushes the oil in the other chamber back to the reservoir. If we assume that the oil pressure in the piston rod chamber is approximately zero, the force F on the piston rod equals the pressure P in the cylinder times the piston area A :

$$\text{Push Force, } F = P \cdot A \quad (1)$$

The piston moves downwards if oil is pumped into the piston rod side chamber and the oil from the bottom chamber area flows back to the reservoir without pressure.

The fluid pressure in the piston rod area chamber is: (Pull Force) / (piston area - piston rod area):

$$P = \frac{F_p}{A_p - A_r} \quad (2)$$

Thus the Pull Force, $F_p = P(A_p - A_r)$ (3)

Where P is the fluid pressure, F_p is the pulling force, A_p is the piston face area and A_r is the rod cross-section area.

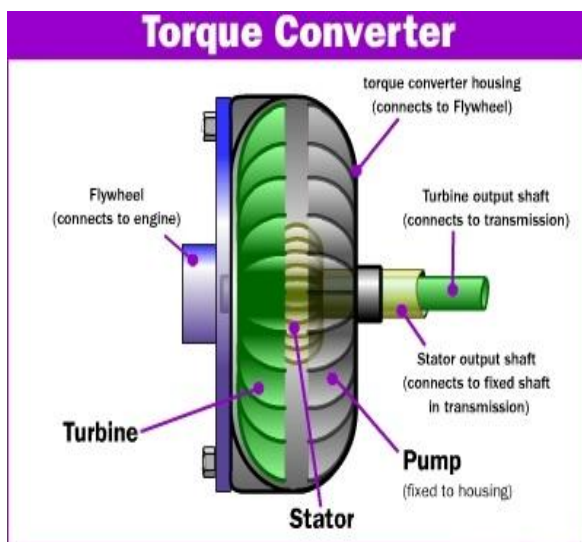
IV.2. TORQUE CONVERTER

An engine is connected to a transmission by way of a clutch. Without this connection, a car would not be able to come to a complete stop without killing the engine. But cars with CVT have no clutch that disconnects the transmission from the engine. Instead, they use an amazing device called a **torque converter**.

As shown in the figure below, there are four components inside the very strong housing of the torque converter:

- **Pump**
- **Turbine**
- **Stator**
- **Transmission fluid**

The **housing** of the torque converter is bolted to the flywheel of the engine, so it turns at whatever speed the engine is running at. The **fins** that make up the pump of the torque converter are attached to the housing, so they also turn at the same speed as the engine. The cutaway below shows how everything is connected inside the torque converter.



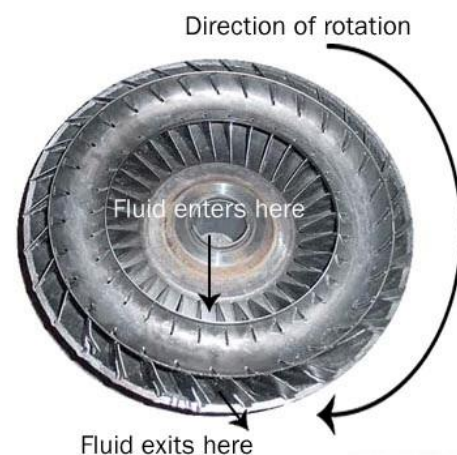
Fig(3): Torque Converter.

The **pump** inside a torque converter is a type of centrifugal pump. As it spins, fluid is flung to the outside, much as the spin cycle of a washing machine flings water and clothes to the outside of the wash tub. As fluid is flung to the outside, a vacuum is created that draws more fluid in at the center.

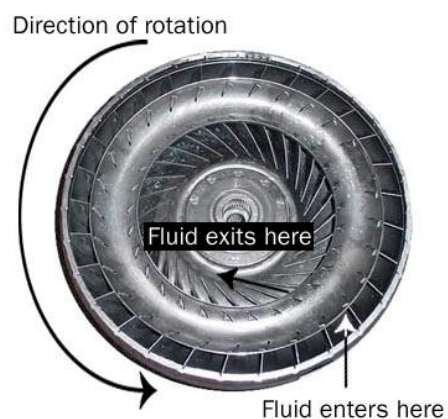
The fluid then enters the blades of the **turbine**, which is connected to the transmission. The turbine causes the transmission to spin, which basically moves your car. You can see in the graphic below that the blades of the turbine are curved. This means that the fluid, which enters the turbine from the outside, has to change direction before it exits the center of the turbine. It is this **directional change** that causes the turbine to spin.

In order to change the direction of a moving object, you must apply a force to that object. And whatever applies the force that causes the object to turn must also feel that force, but in the opposite direction. So as the turbine causes the fluid to change direction, the fluid causes the turbine to spin.

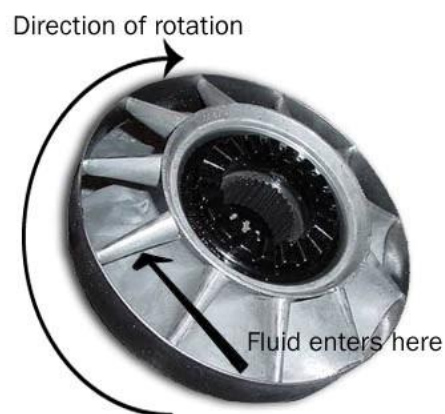
The fluid exits the turbine at the center, moving in a different direction than when it entered. If we look at the arrows in the figures (4) & (5) below, we can see that the fluid exits the turbine moving opposite the direction that the pump (and engine) is turning. If the fluid were allowed to hit the pump, it would slow the engine down, wasting power. This is why a torque converter has a **stator**.



Fig(4): Pump.



Fig(5): Turbine.



Fig(6): Stator

The stator resides in the very center of the torque converter. Its job is to redirect the fluid returning from the turbine before it hits the pump again. This dramatically increases the efficiency of the torque converter.

The stator has a very aggressive blade design that almost completely reverses the direction of the fluid. A one-way clutch (inside the stator) connects

the stator to a fixed shaft in the transmission (the direction that the clutch allows the stator to spin is noted in the fig(6) above). Because of this arrangement, the stator cannot spin with the fluid -- it can spin only in the opposite direction, forcing the fluid to change direction as it hits the stator blades.

V. BELT DESIGN

As the belt is the highly stressed member, it must be very strong and grip very well on the pulleys.

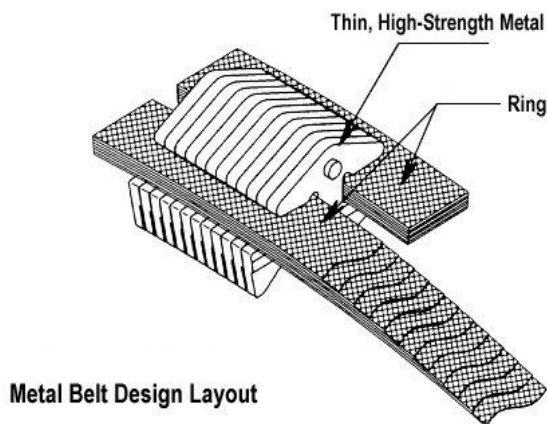
V.1. BELT MATERIALS

1. Rubber.
2. Steel.
3. Thin & high strength Metals.

The variable-diameter pulleys are the heart of a CVT. Each pulley is made of **two 20-degree cones** facing each other. A belt rides in the groove between the two cones. V-belts are preferred if the belt is made of rubber. V-belts get their name from the fact that the belts bear a V-shaped cross section, which increases the frictional grip of the belt.

In earlier applications of the CVT, the transmissions have relied on high-density rubber belts, which can slip and stretch, thereby reducing their efficiency.

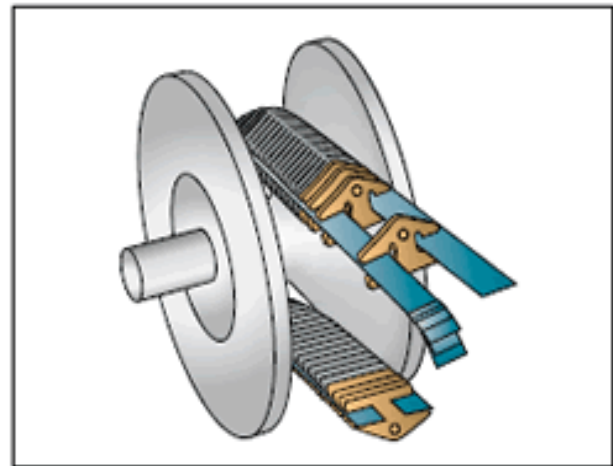
The introduction of new materials makes CVTs even more reliable and efficient. One of the most important advances has been the design and development of metal belts to connect the pulleys. These flexible belts are composed of several (typically nine or 12) thin bands of steel that hold together high-strength, bow-tie-shaped pieces of metal. Metal belts don't slip and are highly **durable**, enabling CVTs to handle more engine torque. They are also **quieter** than rubber-belt-driven CVTs.



Fig(7): Metal Belt Design Layout.

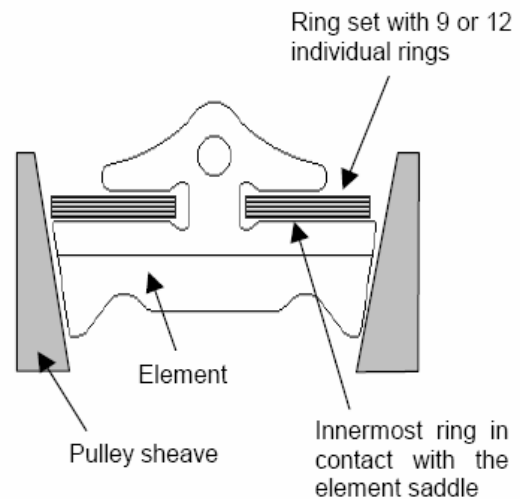


Fig(8): Photograph of a Metal Belt.



Fig(9): Mounting a metal belt on the Pulley.

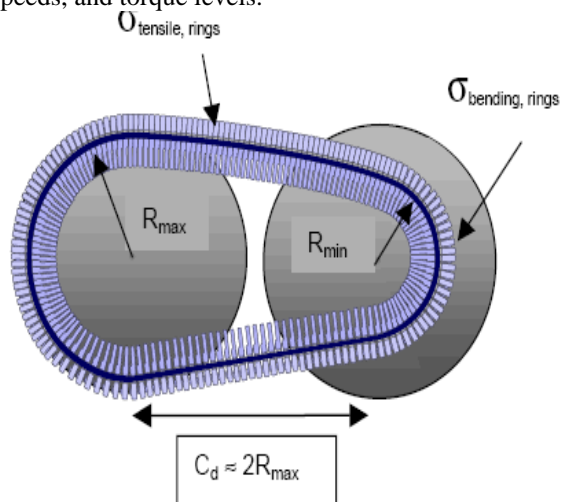
As shown in the figures(7), (8) & (9) above, a CVT belt is constructed by stacking up 9 to 12 Steel bands (called "**Rings**") in the grooves on either sides of a thin high strength metal known as the "**Element**".



Fig(10): Cross section of the Push belt/Pulley system.

V.2. STRESS CONSIDERATIONS

Stepless shifting between the extreme LOW (under drive) and OD (overdrive) ratios is achieved by varying the pulley clamping forces and thereby changing the axial position of the moveable pulley sheaves, modifying the effective running radius. During operation of the variator, the push-belt and pulleys undergo cyclic (fatigue) loading. Stress levels in the push-belt elements and pulleys are determined by the applied pulley clamping forces, rotational speeds, and torque levels. Experience has shown that fatigue loading of the elements and pulleys is less critical in practice than ring fatigue loading. The push-belt rings are mainly subjected to bending and tensile stresses (see Figure11 below). In general, the bending stresses are determined by the applied running radii (transmission ratio) and the ring thickness. The tensile stresses are mainly determined by the applied pulley clamping forces, rotational speeds, and torque levels.



Fig(11): Push-belt loading (ring stresses, running radii, pulley centre distance, ratio coverage).

A film of lubricant is applied to the pulleys. It needs to be thick enough so that the pulley and the belt never touch and it must be thin in order not to waste power when each element dives into the lubrication film. Additionally, the chain elements stabilize about 12 steel bands. Each band is thin enough so that it bends easily. If bending, it has a perfect conical surface on its side. In the stack of bands each band corresponds to a slightly different gear ratio, and thus they slide over each other and need oil between them.

CVT stands for continuously variable transmission. This type of transmission allows for a change in ratios without stopping or disengaging. Most CVT's are friction drive, with some means of varying the relative diameters of the driving components while driving. These friction drive transmissions are simple, but can only transmit a

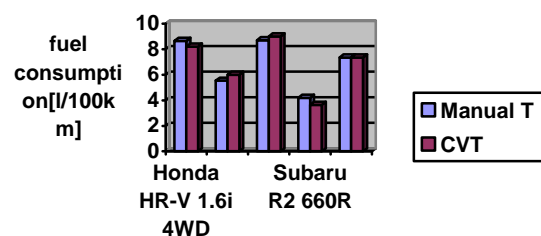
limited amount of torque before the wheels start slipping. There are some CVT's that use gears and cranks that offer positive drive without a chance for slippage, but these are much more complicated.

VI. ADVANTAGES OF CVT

1. CVTs provide unlimited gear ratios and improved performance.
2. Pulleys and a belt inside the CVT seamlessly change the gear ratios without any "shift shock" or delay.
3. The infinite ratios help in maintaining a steady cruising speed, reducing the fuel emissions and thus improve fuel economy.
4. Due to its ability to change the ratios continuously, a CVT helps to keep the engine in its optimum rpm range, thereby increasing the fuel efficiency.
5. The 2012 model of the Honda Jazz sold in the UK actually claims marginally better fuel consumption for the CVT version than the manual version.
6. CVTs provide quicker acceleration than a conventional automatic.
7. A key advantage of a CVT for a manufacturer is that its production costs lesser than a conventional multispeed automatic because it uses fewer parts.
8. CVT eliminates the gear shifts of a manual transmission and the accompanying rise and fall of engine speed.

Fig(12):

Comparison Manual Transmission (MT) versus CVT for a drive cycle.



The Above Graph shows the Fuel Efficiency comparison of the following vehicles:

1. Honda HR-V 1.6i 4WD
2. Honda Jazz 1.4i
3. Nissan Primera 2.0
4. Subaru R2 660R
5. Mercedes Benz A-class A200

VII. LIMITATIONS OF CVT

1. CVTs use steel metal belts, which have less torque transmitting capacity and thus a CVT cannot be used in heavy vehicles. Its application is limited to small vehicles.
2. Friction between the belt and the pulley causes greater wear.
3. The transmission fluid is a little expensive.

VIII. HISTORY

1490 - Leonardo da Vinci sketches a stepless continuously variable Transmission.

1886 - First toroidal CVT patent filed.

1935 - Adiel Dodge receives U.S. patent for toroidal CVT.

1939 - Fully automatic transmission based on planetary gear system introduced.

1958 - Daf (of the Netherlands) produces a CVT in a car.

1989 - Subaru Justy GL is the first U.S. sold production automobile to offer a CVT.

2002 - Saturn Vue(General Motors' SUV) with a CVT debuts.

2004 - Ford begins offering a CVT.

IX. CONCLUSION

"A Continuously Variable Transmission or CVT blends the ease of an automatic transmission with the efficiency of a manual transmission." This statement made by the Honda Motors completely summarizes the concept of CVT.

CVT is definitely a technology of the future with its higher fuel efficiency, infinite gear ratios, lower manufacturing costs, steady cruising speeds & better acceleration capabilities.

This technology has found such wide applications only recently. Thus most of us have to get used to the dynamics of a CVT-equipped vehicle for its better appreciation.

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