

Continuously Variable Transmissions

An Overview of CVT Research Past, Present, and Future

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Abstract

As the U.S. government enacts new regulations for automotive fuel economy and emissions, the continuously variable transmission, or CVT, continues to emerge as a key technology for improving the fuel efficiency of automobiles with internal combustion (IC) engines. CVTs use infinitely adjustable drive ratios instead of discrete gears to attain optimal engine performance. Since the engine always runs at the most efficient number of revolutions per minute for a given vehicle speed, CVT-equipped vehicles attain better gas mileage and acceleration than cars with traditional transmissions.

CVTs are not new to the automotive world, but their torque capabilities and reliability have been limited in the past. New developments in gear reduction and manufacturing have led to ever-more-robust CVTs, which in turn allows them to be used in more diverse automotive applications. CVTs are also being developed in conjunction with hybrid electric vehicles. As CVT development continues, costs will be reduced further and performance will continue to increase, which in turn makes further development and application of CVT technology desirable.

This paper evaluates the current state of CVTs and upcoming research and development, set in the context of past development and problems traditionally associated with CVTs. The underlying theories and mechanisms are also discussed.

Introduction

After more than a century of research and development, the internal combustion (IC) engine is nearing both perfection and obsolescence: engineers continue to explore the outer limits of IC efficiency and performance, but advancements in fuel economy and emissions have effectively stalled. While many IC vehicles meet Low Emissions Vehicle standards, these will give way to new, stricter government regulations in the very near future. With limited room for improvement, automobile manufacturers have begun full-scale development of alternative power vehicles. Still, manufacturers are loath to scrap a century of development and billions or possibly even trillions of dollars in IC infrastructure, especially for technologies with no history of commercial success. Thus, the ideal interim solution is to further optimize the overall efficiency of IC vehicles.

One potential solution to this fuel economy dilemma is the continuously variable transmission (CVT), an old idea that has only recently become a bastion of hope to automakers. CVTs could potentially allow IC vehicles to meet the first wave of new fuel regulations while development of hybrid electric and fuel cell vehicles continues. Rather than selecting one of four or five gears, a CVT constantly changes its gear ratio to optimize engine efficiency with a perfectly smooth torque-speed curve. This improves both gas mileage and acceleration compared to traditional transmissions.

The fundamental theory behind CVTs has undeniable potential, but lax fuel regulations and booming sales in recent years have given manufacturers a sense of complacency: if consumers are buying millions of cars with conventional transmissions, why spend billions to develop and manufacture CVTs? Although CVTs have been used in automobiles for decades, limited torque capabilities and questionable reliability have inhibited their growth. Today, however, ongoing CVT research has led to ever-more-robust transmissions, and thus ever-more-diverse automotive applications. As CVT development continues, manufacturing costs will be further reduced and performance will continue to increase, which will in turn increase the demand for further development. This cycle of improvement will ultimately give CVTs a solid foundation in the world's automotive infrastructure.

CVT Theory & Design

Today's automobiles almost exclusively use either a conventional manual or automatic transmission with "multiple planetary gear sets that use integral clutches and bands to achieve discrete gear ratios" [3]. A typical automatic uses four or five such gears, while a manual normally employs five or six. The continuously variable transmission replaces discrete gear ratios with infinitely adjustable gearing through one of several basic CVT designs.

Push Belt

This most common type of CVT uses segmented steel blocks stacked on a steel ribbon, as shown in Figure (1). This belt transmits power between two conical pulleys, or sheaves, one fixed and one movable [3]. With a belt drive:

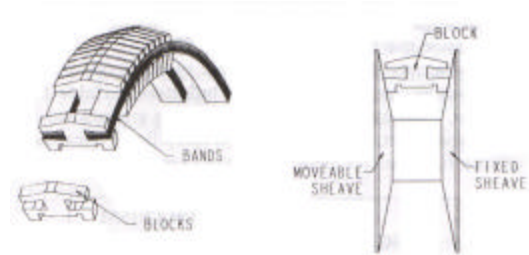


Figure (1) – Metal Push Belt CVT
From [3]

In essence, a sensor reads the engine output and then electronically increases or decreases the distance between pulleys, and thus the tension of the drive belt. The continuously changing distance between the pulleys—their ratio to one another—is analogous to shifting gears. [6]

Push-belt CVTs were first developed decades ago, but new advances in belt design have recently drawn the attention of automakers worldwide.

Toroidal Traction-Drive

These transmissions use the high shear strength of viscous fluids to transmit torque between an input torus and an output torus. As the movable torus slides linearly, the angle of a roller changes relative to shaft position, as seen in Figure (2). This results in a change in gear ratio [3].

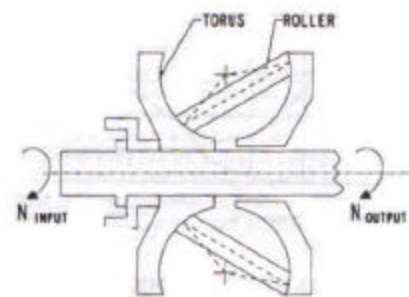


Figure (2) – Toroidal CVT
From [3]

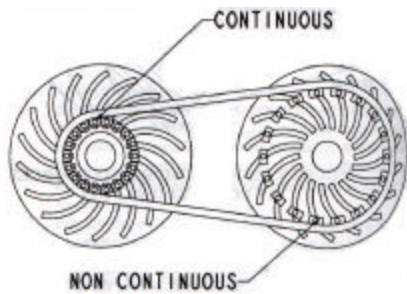


Figure (3) – Variable Diameter Belt CVT
From [3]

Variable Diameter Elastomer Belt

This type of CVT, as represented in Figure (2), uses a flat, flexible belt mounted on movable supports. These supports can change radius and thus gear ratio. However, the supports separate at high gear ratios to form a discontinuous gear path, as seen in Figure (3). This can lead to the problems with creep and slip that have plagued CVTs

for years [3]. This inherent flaw has directed research and development toward push belt CVTs.

Other CVT Varieties

Several other types of CVTs have been developed over the course of automotive history, but these have become less prominent than push belt and toroidal CVTs. A nutating traction drive uses a pivoting, conical shaft to change “gears” in a CVT. As the cones change angle, the inlet radius decreases while the outlet radius increases, or vice versa, resulting in an infinitely variable gear ratio [3]. A variable geometry CVT uses adjustable planetary gearsets to change gear ratios, but this is more akin to a flexible traditional transmission than a conventional CVT.

Background & History

To say that the continuously variable transmission (CVT) is nothing new would be a gross understatement: Leonardo da Vinci sketched his idea for a CVT in 1490 [1]. In automotive applications, CVTs have been around nearly as long as cars themselves, and certainly as long as conventional automatics. General Motors actually developed a fully toroidal CVT in the early 1930s and conducted extensive testing before eventually deciding to implement a conventional, stepped-gear automatic due to cost concerns. General Motors Research worked on CVTs again in the 1960s, but none ever saw production [2]. British manufacturer Austin used a CVT for several years in one of its smaller cars, but “it was dropped due to its high cost, poor reliability, and inadequate torque transmission” [2]. Many early CVTs used a simple rubber band and cone system, like the one developed by Dutch firm Daf in 1958 [1].

However, the Daf CVT could only handle a 0.6 L engine, and problems with noise and rough starts hurt its reputation [1]. Uninspired by these early failures, automakers have largely avoided CVTs until very recently, especially in the United States.

Inherent Advantages & Benefits

Certainly, the clunk of a shifting transmission is familiar to all drivers. By contrast, a continuously variable transmission is perfectly smooth—it naturally changes “gears” discreetly and minutely such that the driver or passenger feels only steady acceleration. In theory, a CVT would cause less engine fatigue and would be a more reliable transmission, as the harshness of shifts and discrete gears force the engine to run at a less-than-optimal speed.

Moreover, CVTs offer improved efficiency and performance. Table (1) below shows the power transmission efficiency of a typical five-speed automatic, i.e. the percentage of engine power translated through the transmission. This yields an average efficiency of 86%, compared to a typical manual transmission with 97% efficiency [3]. By comparison, Table (2) below gives efficiency ranges for several CVT designs.

Table (1) Efficiency vs. Gear Ratio for Automatic Transmission [3]

<u>Gear</u>	<u>Efficiency Range</u>
1	60-85%
2	60-90%
3	85-95%
4	90-95%
5	85-94%

Table (2) Efficiency of Various CVT Designs [3]

<u>CVT Mechanism</u>	<u>Efficiency Range</u>
Rubber Belts	90-95%
Steel Belts	90-97%
Toroidal Traction	70-94%
Nutating Traction	75-96%
Variable Geometry	85-93%

These CVTs each offer improved efficiency over conventional automatic transmissions, and their efficiency depends less on driving habit than manual transmissions [3]. Moreover:

Because the CVT allows an engine to run at this most efficient point virtually independent of vehicle speed, a CVT equipped vehicle yields fuel economy benefits when compared to a conventional transmission... [3]

Testing by ZF Getriebe GmbH several years ago found that “the CVT uses at least 10% less fuel than a 4-speed automatic transmission” for U.S. Environmental Protection Agency city and highway cycles. Moreover, the CVT was more than one second faster in 0-60 mph acceleration tests [5]. The potential for fuel efficiency gains can also be seen in the CVT currently used in Honda’s Civic. A Civic with a

traditional automatic averages 28/35 miles per gallon (mpg) city/highway, while the same car with a CVT gets 34/38 mpg city/highway [4]. Honda has used continuously variable transmissions in the Civic for several years, but these are 1.6 liter cars with limited torque capabilities. Ongoing research and development will inevitably expand the applicability of CVTs to a much broader range of engines and automobiles.

Challenges & Limitations

CVT development has progressed slowly for a variety of reasons, but much of the delay in development can be attributed to a lack of demand: conventional manual and automatic transmissions have long offered sufficient performance and fuel economy. Thus, problems encountered in CVT development usually stopped said progress. “Designers have ... unsuccessfully tried to develop [a CVT] that can match the torque capacity, efficiency, size, weight, and manufacturing cost of step-ratio transmissions” [6].

One of the major complaints with previous CVTs has been slippage in the drive belt or rollers. This is caused by the lack of discrete gear teeth, which form a rigid mechanical connection between to gears; friction drives are inherently prone to slip, especially at high torque. With early CVTs of the 1950s and 1960s, engines equipped with CVTs would run at excessively high RPM trying to “catch up” to the slipping belt. This would occur any time the vehicle was accelerated from a stop at peak torque:

“For compressive belts, in the process of transmitting torque, micro slip occurs between the elements and the pulleys. This micro slip tends to increase sharply once the transmitted torque exceeds a certain value ...” [8]

For many years, the simple solution to this problem has been to use CVTs only in cars with relatively low-torque engines. Another solution is to employ a torque converter (such as those used in conventional automatics), but this reduces the CVT’s efficiency [2].

Perhaps more than anything else, CVT development has been hindered by cost. Low volume and a lack of infrastructure have driven up manufacturing costs, which inevitably yield higher transmission prices. With increased development, most of these problems can be addressed simply by improvements in manufacturing techniques and materials processing. For example, Nissan’s Extroid “is derived from a

century-old concept, perfected by modern technology, metallurgy, chemistry, electronics, engineering, and precision manufacturing” [2].

In addition, CVT control must be addressed. Even if a CVT can operate at the optimal gear ratio at any speed, how does it “know” what ratio to select? Manual transmissions have manual controls, where the driver shifts when he or she so desires; automatic transmissions have relatively simple shifting algorithms to accommodate between three and five gears. However, CVTs require far more complex algorithms to accommodate an infinite division of speeds and gear ratios.

Research & Development

While IC development has slowed in recent years as automobile manufacturers devote more resources to hybrid electric vehicles (HEVs) and fuel cell vehicles (FEVs), CVT research and development is expanding quickly. Even U.S. automakers, who have lagged in CVT research until recently, are unveiling new designs: General Motors plans to implement metal-belt CVTs in some vehicles by 2002 [6].



Figure (4) – GM’s New CVT design
From [6]

The Japanese and Germans continue to lead the way in CVT development. Nissan has taken a dramatic step with its “Extroid” CVT, offered in the home-market Cedric and Gloria luxury sedans. This toroidal CVT costs more than a conventional belt-driven CVT, but Nissan expects the extra cost to be absorbed by the luxury cars’ prices [2]. The Extroid uses a high viscosity fluid to transmit power between the disks and rollers, rather than metal-to-metal contact. Coupled with a torque converter, this yields “exceptionally fast ratio changes”. Most importantly, though, the Extroid is available with a turbocharged version of Nissan’s 3.0 liter V6 producing 285 lb-ft of torque; this is a new record for CVT torque capacity [2].

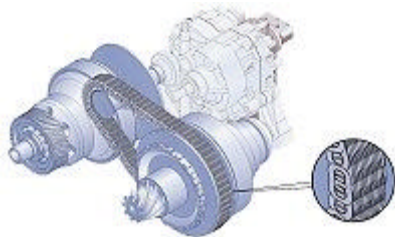


Figure (5) – Audi CVT with link chain
From [1]

Audi’s new CVT offers both better fuel mileage than a conventional automatic and better acceleration than even a

manual transmission. Moreover, Audi claims it can offer the CVT at only a slight price increase [1]. This so-called “multitronic” CVT uses an all-steel link plate chain instead of a V-belt in order to handle up to 280 lb-ft of torque [1]. In addition, “Audi claims that the multitronic A6 accelerates from 0-100 km/h (0-62 mph) 1.3 s quicker than a geared automatic transmission and is 0.1 s quicker over the same speed than an equivalent model with “optimum” use of a five speed manual gearbox” [1]. If costs were sufficiently reduced, a transmission such as this could be used in almost any automobile in the world.

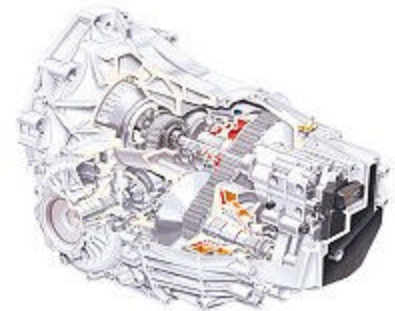


Figure (6) – Cutaway of Audi CVT From [1]

Many small cars have used CVTs in recent years, and many more will use them in the near future. Nissan, Honda, and Subaru currently use belt-drive CVTs developed with Dutch company Van Doorne Transmissie (VDT) in some of their smaller cars [7]. Suzuki and Daihatsu are jointly developing CVTs with Japanese company Aichi Machine, using an aluminum/plastic composite belt reinforced with Aramid fibers. Their CVT uses an auxiliary transmission for starts to avoid low-speed slip. After about 6 mph, the CVT engages and operates as it normally would [7]. “The auxiliary geartrain’s direct coupling ensures sufficiently brisk takeoff and initial acceleration” [7]. However, Aichi’s CVT can only handle 52 lb-ft of torque. This alone effectively negates its potential for the U.S. market. Still, there are far more CVTs in production for 2000 than for 1999, and each major automobile show brings more announcements for new CVTs.

New CVT Research

As recently as 1997, CVT research focused on the basic issues of drive belt design and power transmission. Now, as belts by VDT and other companies become sufficiently efficient, research focuses primarily on control and implementation of CVTs.

Nissan Motor Co. has been a leader in CVT research since the 1970s. A recent study analyzing the slip characteristics of a metal belt CVT resulted in a simulation method for slip limits and torque capabilities of CVTs [8]. This has led to a dramatic improvement in drive belt technology, since CVTs can now be modeled and analyzed with computer simulations, resulting in faster development and more

efficient design. Nissan's research on the torque limits of belt-drive CVTs has also led to the use of torque converters, which several companies have since implemented. The torque converter is designed to allow "creep," the slow speed at which automatic transmission cars drive without driver-induced acceleration. The torque converter adds "improved creep capability during idling for improved driveability at very low speeds and easy launch on uphill grades" [9]. Nissan's Extroid uses such a torque converter for "smooth starting, vibration suppression, and creep characteristics" [2].

CVT control has recently come to the forefront of research; even a mechanically perfect CVT is worthless without an intelligent active control algorithm. Optimal CVT performance demands integrated control, such as the system developed by Nissan to "obtain the demanded drive torque with optimum fuel economy" [13]. The control system determines the necessary CVT ratio based on a target torque, vehicle speed, and desired fuel economy. Honda has also developed an integrated control algorithm for its CVTs, considering not only the engine's thermal efficiency but also work loss from drivetrain accessories and the transmission itself [12]. Testing of Honda's algorithm with a prototype vehicle resulted in a one percent fuel economy increase compared to a conventional algorithm. While not a dramatic increase, Honda claims that its algorithm is fundamentally sound, and thus will it become "one of the basic technologies for the next generation's powerplant control" [12].

Although CVTs are currently in production, many control issues still amount to a "tremendous number of trials and errors" [10]. One study focusing on numerical representation of power transmission showed that "both block tilting and pulley deformation meaningfully effected the pulley thrust ratio between the driving and the driven pulleys" [10]. Thus, the resultant model of CVT performance can be used in future applications for transmission optimization. As more studies are conducted, fundamental research such as this will become the legacy of CVT design, and research can become more specialized as CVTs become more refined.

As CVTs move from research and development to assembly line, manufacturing research becomes more important. CVTs require several crucial, high-tolerance components in order to function efficiently; Honda studied one of these, the pulley piston, in 1998. Honda found that prototype pistons

“experienced a drastic thickness reduction (32% at maximum) due to the conventional stretch forming method” [11]. A four-step forming process was developed to ensure “a greater and more uniform thickness increase” and thus greater efficiency and performance. Moreover, work-hardening during the forming process further increased the pulley piston’s strength [11].

Size and weight of CVTs has long been a concern, since conventional automatics weigh far more than manual transmissions and CVTs outweigh automatics. Most cars equipped with automatic transmissions have a curb weight between 50 and 150 pounds heavier than the same cars with manual transmissions. To solve this problem, Audi is currently developing magnesium gearbox housings, a first for cars in its class. This results in nearly a 16 pound weight reduction over conventional automatics. [1].

Future Prospects for CVTs

Much of the existing literature is quick to admit that the automotive industry lacks a broad knowledge base regarding CVTs. Whereas conventional transmissions have been continuously refined and improved since the very start of the 20th century, CVT development is only just beginning. As infrastructure is built up along with said knowledge base, CVTs will become ever-more prominent in the automotive landscape. Even today’s CVTs, which represent first-generation designs at best, outperform conventional transmissions. Automakers who fail to develop CVTs now, while the field is still in its infancy, risk being left behind as CVT development and implementation continues its exponential growth. Moreover, CVTs are do not fall exclusively in the realm of IC engines.

CVTs & Hybrid Electric Vehicles

While CVTs will help to prolong the viability of internal combustion engines, CVTs themselves will certainly not fade if and when IC does. Several companies are currently studying implementation of CVTs with HEVs. Nissan recently developed an HEV with “fuel efficiency ... more than double that of existing vehicles in the same class of driving performance” [14]. The electric motor avoids the low-speed/high torque problems often associated with CVTs, through an innovative double-motor system. At low speeds:

A low-power traction motor is used as a substitute mechanism to accomplish the functions of launch and forward/reverse shift. This has made it possible to discontinue

use of a torque converter as the launch element and a planetary gearset and wet multiplate clutches as the shift mechanism. [14]

Thus use of a CVT in a HEV is optimal: the electric portion of the power system avoids the low-speed problems of CVTs, while still retaining the fuel efficiency and power transmission benefits at high speeds.. Moreover, “the use of a CVT capable of handling high engine torque allows the system to be applied to more powerful vehicles” [14]. Obviously, automakers cannot develop individual transmissions for each car they sell; rather, a few robust, versatile CVTs must be able to handle a wide range of vehicles.

Korean automaker Kia has proposed a rather novel approach to CVTs and their application to hybrids. Kia recently tested a system where “the CVT allows the engine to run at constant speed and the motor allows the engine to run at constant torque independent of driving conditions” [15]. Thus, both gasoline engine and electric motor always run at their optimal speeds, and the CVT adjusts as needed to accelerate the vehicle. Kia also presented a control system for this unified HEV/CVT combination that optimizes fuel efficiency for the new configuration.

Conclusion

Today, only a handful of cars worldwide make use of CVTs, but the applications and benefits of continuously variable transmissions can only increase based on today’s research and development. As automakers continue to develop CVTs, more and more vehicle lines will begin to use them. As development continues, fuel efficiency and performance benefits will inevitably increase; this will lead to increased sales of CVT-equipped vehicles. Increased sales will prompt further development and implementation, and the cycle will repeat ad infinitum. Moreover, increasing development will foster competition among manufacturers—automakers from Japan, Europe, and the U.S. are already either using or developing CVTs—which will in turn lower manufacturing costs. Any technology with inherent benefits will eventually reach fruition; the CVT has only just begun to blossom.

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