■ Abstract

In their pursuit of continuously realizing better automobiles, engineers in Japan's automotive industry have relentlessly advanced the diverse technologies underpinning vehicle materials, components, and units. This evolution has been characterized by a persistent history of engineers seeking out seeds of innovation from across the globe, or cultivating their own, and nurturing them through long-term, steadfast research and development to bring these technologies to maturity.

In the 1970s, propelled by rapid economic growth, Japan's automotive industry grappled with the problem of harmful exhaust emissions from automotive internal combustion engines. Concurrently, the rise in female drivers made the development of easier-to-drive vehicles an urgent necessity. In the Japanese market of that era, manual transmissions (MT) were the mainstream choice for automotive gearboxes. Automatic transmissions (AT), while dominant in the US market, were found in Japan primarily on large luxury-class vehicles.

Against this backdrop, the practical implementation of the Continuously Variable Transmission (CVT) gained significant attention as the ideal automatic transmission. By maintaining the internal combustion engine in an optimal operating state via its continuously variable gear ratios, the CVT promised improvements in both emissions and fuel economy. Furthermore, it offered the prospect of easier driving through seamless, uninterrupted gear shifts.

Reflecting on the technological transition from horse-drawn carriages to automobiles, the first manual transmission appeared in 1886 on an internal combustion engine vehicle introduced by Daimler. Prior to that, electric vehicles had been unveiled in 1884, and steam-powered vehicles invented as early as 1769. Crucially, neither of these earlier forms required a transmission. This history underscores that, from 1886 onward, the transmission established itself as an essential and indispensable power transmission mechanism specifically for the internal combustion engine automobile.

The world's first automotive continuously variable transmission was the Reeves CVT, announced in 1897 by the US-based Reeves Motor Company. This CVT employed a belt constructed from a leather-and-rubber band, with wooden blocks fastened by bolts. Owing to inadequate durability, a limitation inherent in its material strength, this design could not withstand the increasing output torque of internal combustion engines and eventually vanished from the market. Yet, the very fact that a CVT-equipped vehicle was commercialized in the United States in 1897, a mere 11 years after the manual transmission's automotive debut in 1886, demonstrates that the technical merit of continuously variable shifting was already acknowledged in vehicle manufacturing approximately 130 years ago.

In 1958, a vehicle fitted with a dry rubber V-belt CVT was commercialized in the Netherlands. By the 1970s, approximately 900,000 of these CVT-specific dry V-belts had been manufactured. This milestone marks the dawn of the mass-production era for passenger cars equipped with continuously variable transmissions.

From the 1960s onward, the dynamic performance afforded by continuously variable transmissions was highly valued, leading to their adoption in formula and rally cars. However, constrained by the inherent torque capacity limits of the dry rubber V-belt, this type of CVT was only applicable to internal combustion engines with displacements up to approximately 0.8 liters. Consequently, vehicle production featuring these units eventually ceased. For CVT technology, the issue of insufficient torque capacity thus persisted as the second major, and seemingly unavoidable, technical hurdle.

In the 1970s, Van Doorne's Transmissie b.v. of the Netherlands made significant strides in the fundamental research, practical development, and production preparation for a metal V-belt. This groundwork culminated in 1987 when Fuji Heavy Industries, Ltd. (now Subaru Corporation) commenced mass production of vehicles equipped with the ECVT; the world's first practical automotive metal V-belt CVT. Serving as a critical benchmark, the ECVT propelled CVT development by automakers and transmission suppliers from a nascent, experimental phase into a period of intense and rapid advancement.

Upon entering an accelerated phase of development starting in 1997, a new type of continuously variable transmission emerged, conceived from the outset as a replacement for the US-originated planetary-gear automatic transmission. These CVTs featured an increased torque capacity suitable for engines up to

2.0 liters in displacement and, in a first for the technology, incorporated a torque converter as the launch element. This era also coincided with the full integration of electronic control for CVTs, mirroring the broader trend toward vehicle-wide electronic management systems.

Thus, the synergistic combination of electronic throttle control for the internal combustion engine and electronic shift control for the CVT enabled the precise, nuanced management of tire driving and braking force. This gave rise to the Hyper CVT, developed by Nissan Motor Co., Ltd. Situated between the rotational energy of the engine and the driving force at the tires, the CVT began to be regarded from this period onward as the central command unit for managing the vehicle's kinetic energy. With the advancement of CVTs designed for automotive electrification, the technology was poised to chart a definitive course toward supplanting conventional automatic transmissions altogether.

The 2000s saw the emergence of the dual-clutch transmission (DCT), a technology with European origins. Although a later entrant than the CVT, the DCT's construction, based on the parallel-shaft gear train of a manual transmission, gave it inherent advantages for increasing the number of discrete gear ratios and widening the overall ratio spread, positioning it as a direct competitor. Furthermore, CVTs, which rely on metal-to-metal frictional contact between a belt and pulleys for power transfer, suffered from a comparative disadvantage in drivetrain efficiency against both planetary-gear automatics and DCTs, which utilize the positive engagement of meshing gears. Thus, CVTs found themselves engaged in a three-way battle for market supremacy against the established US-born planetary automatic and the newer European DCT.

From 2007 onward, a period of further development saw the successive introduction of compound CVT designs. These systems incorporated a supplementary gearset into the metal V-belt drivetrain. This integration of gearing contributed not only to a wider overall ratio spread but also to enhanced transmission efficiency and greater torque capacity. In parallel, for conventional (non-geared) CVT designs, the practical adoption of V-chains expanded as a replacement for metal V-belts, primarily to achieve higher torque capacity.

Following the successful implementation of the V-chain in Japanese CVTs in 2009, torque capacity expanded to 380 Nm, making it suitable for engines in the 3.8-liter class. Annual production volume subsequently reached approximately 10 million units, solidifying the CVT's status as a fully established and legitimate automatic transmission technology.

Entering a phase of maturity from 2017 onward, CVTs attained parity with planetary-gear automatics and dual-clutch transmissions in both torque-handling capacity and overall ratio spread. A landmark was reached in 2021 when the average drivetrain efficiency of CVTs, measured under standardized fuel economy test cycles, achieved 90%.

In this way, through roughly forty years of sustained development for practical application, spanning from 1987 to the present, the continuously variable transmission, cultivated by Japan's automotive industry as a novel automatic transmission technology, has achieved global market proliferation.

This systematic survey is limited to V-belt and V-chain type continuously variable transmissions. The toroidal CVT, adopted by only a single manufacturer, falls outside its scope.

The global automotive industry is now navigating a once-in-a-century transformation. With vehicle electrification advancing at a rapid pace, the CVT, long an indispensable partner to the internal combustion engine, has reached a critical inflection point. The diverse technologies inherent in CVTs, which integrate precision mechanical components with sophisticated control systems and were honed through complex vehicle integration, will undoubtedly find new applications. They are poised to contribute to the ongoing development of key electrification components such as electric motors, generators, reduction gears, power electronics (inverters), and battery thermal management systems.