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A Review of Continuously Variable Transmissions: Classification and Performance Analysis

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Abstract

Continuously variable transmissions (CVTs) have become an important element of modern powertrain systems due to their ability to provide smooth ratio variation and improve overall energy efficiency. However, the term "CVT" is often used in a narrow sense, typically referring only to belt or chain variators, while a broader range of transmission concepts remains insufficiently systematized. This lack of a unified classification complicates the comparison and selection of transmission systems for different applications. The present paper aims to provide a comprehensive overview of continuously variable transmissions based on their operating principles and to develop a unified framework for their classification and comparison. The study considers friction-based mechanical CVTs, hydrostatic and hydromechanical transmissions, electromechanical power-split systems, as well as emerging technologies such as magnetic and traction-drive transmissions. A set of key performance parameters is introduced, including transmission ratio range, torque and power capacity, efficiency, dynamic response, structural characteristics, and control complexity. Based on these parameters, a comparative analysis of the main CVT types is performed and summarized in a structured table. The results show that each transmission type exhibits specific advantages and limitations depending on its physical operating principle. Friction-based systems offer compactness and relatively high efficiency, while hydrostatic and hydromechanical transmissions provide superior torque capacity and controllability. Electromechanical CVTs demonstrate high flexibility in hybrid systems, whereas emerging technologies show potential for further improvement. It is concluded that no single CVT type can be considered universally optimal, and the selection of a transmission system must be based on specific application requirements. The proposed classification and comparative framework can be used as a basis for the design and selection of CVT systems in modern engineering applications.

Index Terms

Continuously variable transmission; CVT; transmission classification; hydrostatic transmission; power-split transmission; traction drive; transmission efficiency; torque capacity; hybrid powertrain

I. INTRODUCTION

Modern engineering systems increasingly demand flexible and energy-efficient power transmission solutions. This is especially true in automotive engineering, agricultural machinery, and hybrid powertrains, where operating conditions vary continuously rather than discretely. Traditional stepped transmissions, despite their robustness and widespread use, are inherently limited by fixed gear ratios. They cannot always ensure optimal engine operation under changing load and speed conditions. Because of this, continuously variable transmissions (CVTs) have attracted significant attention over the past decades [3,10]. They allow smooth variation of the transmission ratio within a certain range. No steps. No interruptions in torque flow. In theory, this enables the prime mover to operate closer to its optimal efficiency point at all times. However, the term "CVT" is often used in a narrow sense, typically referring only to belt or chain variators [10] used in passenger vehicles. This is not entirely correct. In a broader engineering context, continuously variable transmissions include several fundamentally different concepts [3,14] there is no single unified view on classification. Some of them rely on frictional contact. Others use hydraulic power flow. There are also electromechanical systems, where part of the power is converted into electrical energy and vice versa. This diversity creates a problem. There is no single unified view on classification [3,14]. Different authors group these transmissions differently. Sometimes hydrostatic systems are included in CVTs, sometimes they are treated separately. The same applies to power-split and hybrid transmissions. As a result, comparison between different technologies becomes complicated. Another issue is the lack of consistent parameter-based analysis. Many publications describe individual transmission types in detail, but only a limited number of studies attempt to compare them [10,11,16] using a unified set of performance criteria. At the same time, recent studies have focused on specific aspects of transmission systems, including advanced coatings, tribological effects, and integration of CVT systems in renewable energy applications [12,17,26,27]. However, these works are typically limited to particular components or operating conditions and do not provide a unified framework for comparing different types of continuously variable transmissions. Efficiency is often discussed. Torque capacity too. But rarely together, and almost never across all major CVT classes. At the same time, such comparison is important. Engineers need to understand not only how a transmission works, but also where it performs best. And where it does not. For example, hydrostatic transmissions provide excellent control [8,20] at low speeds, but suffer from lower efficiency at high speeds. Belt CVTs are compact [10] and relatively simple, yet limited in torque capacity. Power-split systems show high efficiency [14,22], but their structure is complex and expensive. So there is a gap. Not in theory, but in systematization. The objective of this paper is to provide a structured overview of the main types of continuously variable transmissions and to compare them based on a unified set of key performance parameters. The study includes friction-based CVTs, hydrostatic and hydromechanical transmissions, electromechanical power-split systems, as well as several emerging technologies. The analysis focuses on parameters such as transmission ratio range, torque and power capacity, efficiency, dynamic response, structural complexity, and application fields. A comparative table is developed to summarize the main characteristics of each transmission type. The results of this study can be useful for both researchers and engineers involved in the design and selection of transmission systems. Especially in applications where efficiency and adaptability are critical.

II. CLASSIFICATION OF CONTINUOUSLY VARIABLE TRANSMISSIONS

The classification of continuously variable transmissions remains a somewhat debated topic in engineering literature [3,10]. Different authors tend to group these systems based on application, design features, or historical development. However, such approaches often lead to inconsistencies, especially when comparing fundamentally different transmission concepts. In this study, a functional classification is adopted, where CVTs are grouped according to the dominant mechanism of power transmission. This allows a more consistent comparison between systems that may differ significantly in structure but serve similar purposes. The resulting classification is presented in Fig. 1.

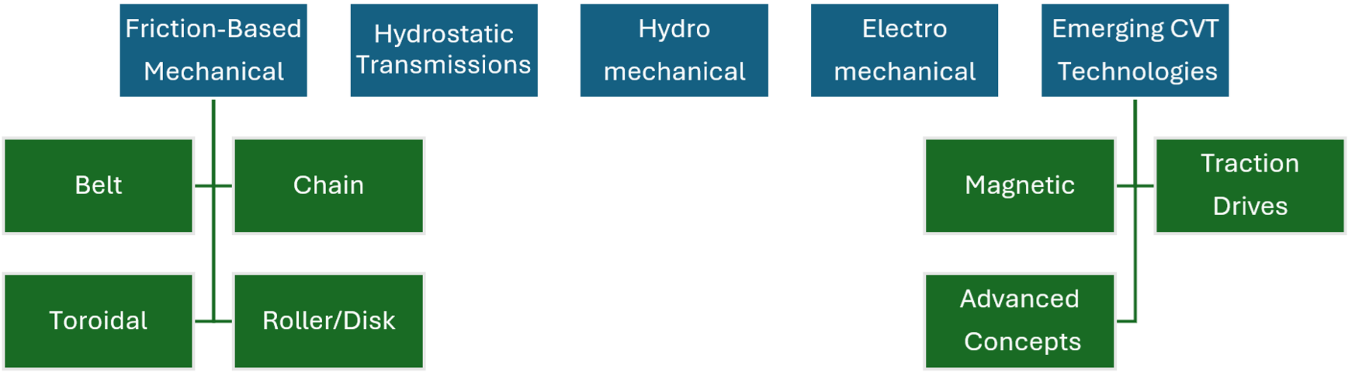

Fig. 1. Classification of Continuously Variable Transmissions.

As shown in Fig. 1, all continuously variable transmissions considered in this work are divided into five main groups: friction-based mechanical CVTs, hydrostatic transmissions, hydromechanical CVTs, electromechanical CVTs, and emerging CVT technologies. Each group is briefly discussed below.

A. Friction-Based Mechanical CVTs

Friction-based CVTs represent the most widely recognized class of continuously variable transmissions. These systems transmit torque through direct mechanical contact between elements, typically using friction or traction forces. The main subtypes include belt CVTs, chain CVTs, toroidal CVTs, and roller or disk-type mechanisms, as illustrated in Fig. 1. Despite differences in design, all of them operate based on a similar principle: the transmission ratio is varied by changing the geometry of the contact interface. A typical example is shown in Fig. 2, where a belt-type CVT uses two pulleys with variable effective diameters. By adjusting the pulley spacing, the belt position changes, which leads to a continuous variation of the transmission ratio.

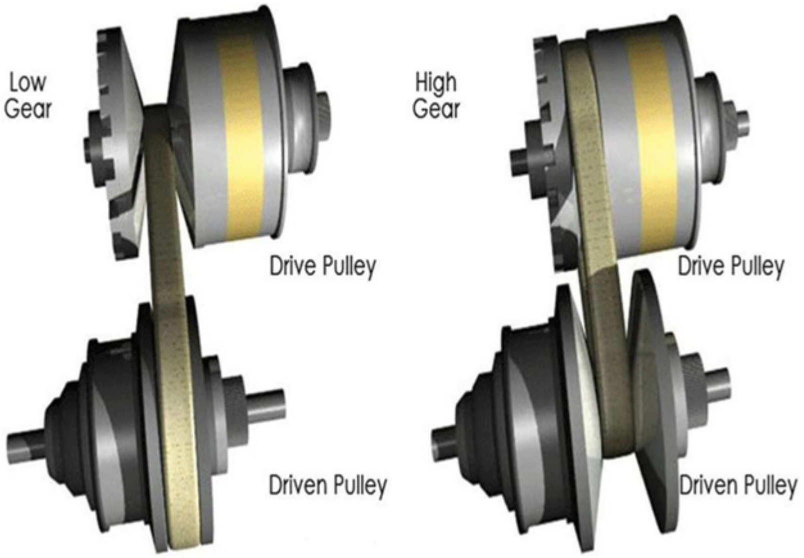

Fig. 2. Friction-Based CVT (Belt / Chain).

These systems are compact and relatively efficient, making them suitable for automotive applications. However, their performance is strongly influenced by contact conditions, and wear remains an important factor affecting durability.

B. Hydrostatic Transmissions

Hydrostatic transmissions operate on a completely different principle compared to mechanical CVTs. Instead of direct contact, power is transmitted through a hydraulic fluid [8,9]. As illustrated in Fig. 3, the system typically consists of a variable-displacement pump and a hydraulic motor connected in a closed loop. By adjusting the displacement of the pump or motor, the flow rate changes, which directly affects the output speed and torque.

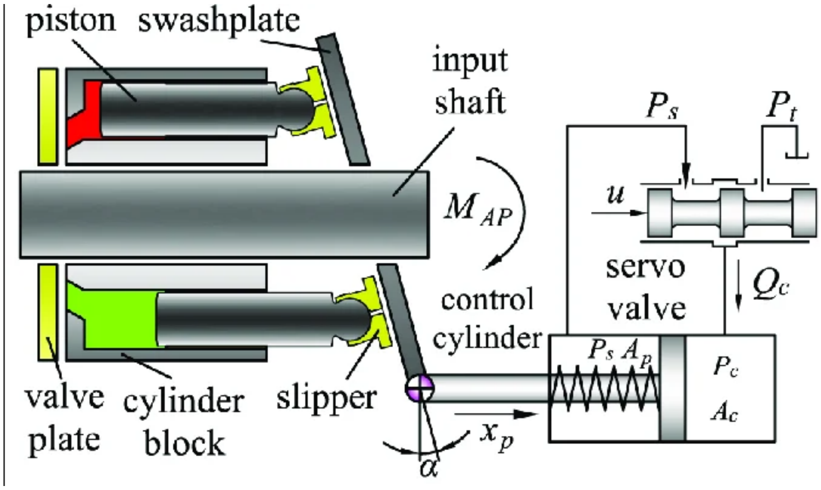

Fig. 3. Hydrostatic Transmission.

One key advantage of hydrostatic systems is the ability to achieve zero output speed while maintaining engine operation. This provides excellent controllability, especially in low-speed, high-load conditions. At the same time, energy losses in the fluid reduce efficiency, particularly at higher speeds. So the system is powerful. But not always efficient.

C. Hydromechanical CVTs

Hydromechanical transmissions combine mechanical and hydraulic power paths in a single system. The goal is simple: improve efficiency while retaining the flexibility of hydrostatic control [14,19].

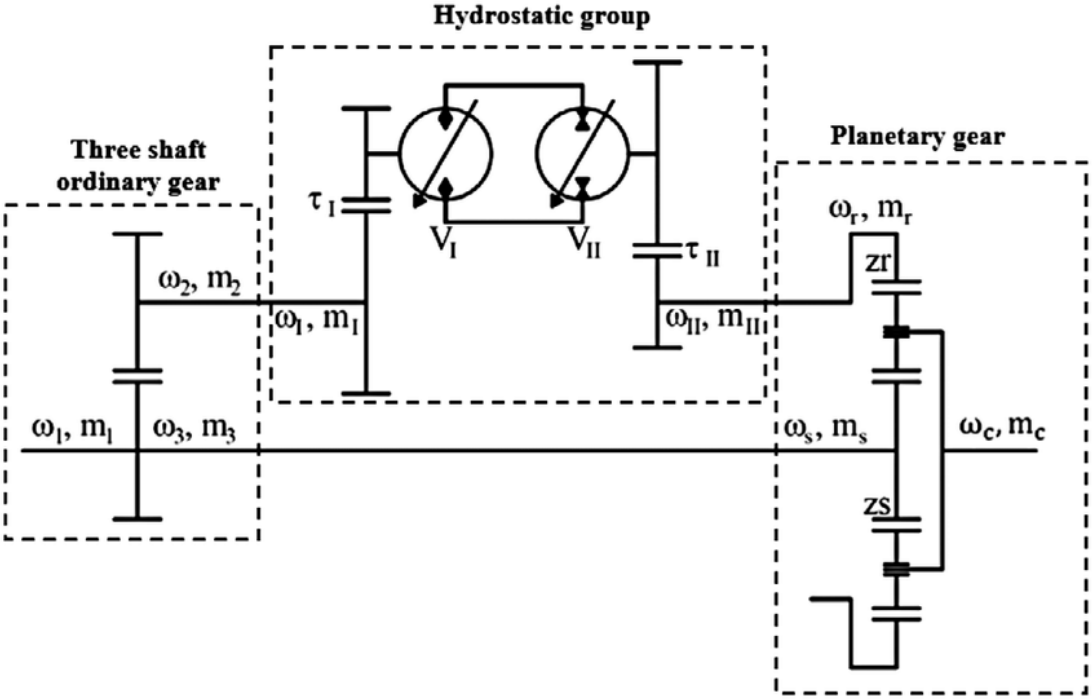

Fig. 4. Hydromechanical CVT (Power Split).

In these systems, power is divided into two branches — a mechanical path and a hydrostatic path — and later recombined. This concept is typically implemented using a planetary gear set, as shown in Fig. 4. Only part of the power flows through the hydraulic system, which reduces overall losses compared to purely hydrostatic transmissions. At the same time, continuous ratio variation is preserved. The concept is effective. But the structure becomes more complex. Control is also more demanding.

D. Electromechanical CVTs

Electromechanical CVTs, often referred to as power-split transmissions, introduce electrical energy conversion into the system. As illustrated in Fig. 5, mechanical power from the engine is divided into two paths. One path is transmitted directly through a mechanical connection. The other drives an electric generator, which produces electrical energy to power an electric motor. The outputs of both paths are then combined [22,25].

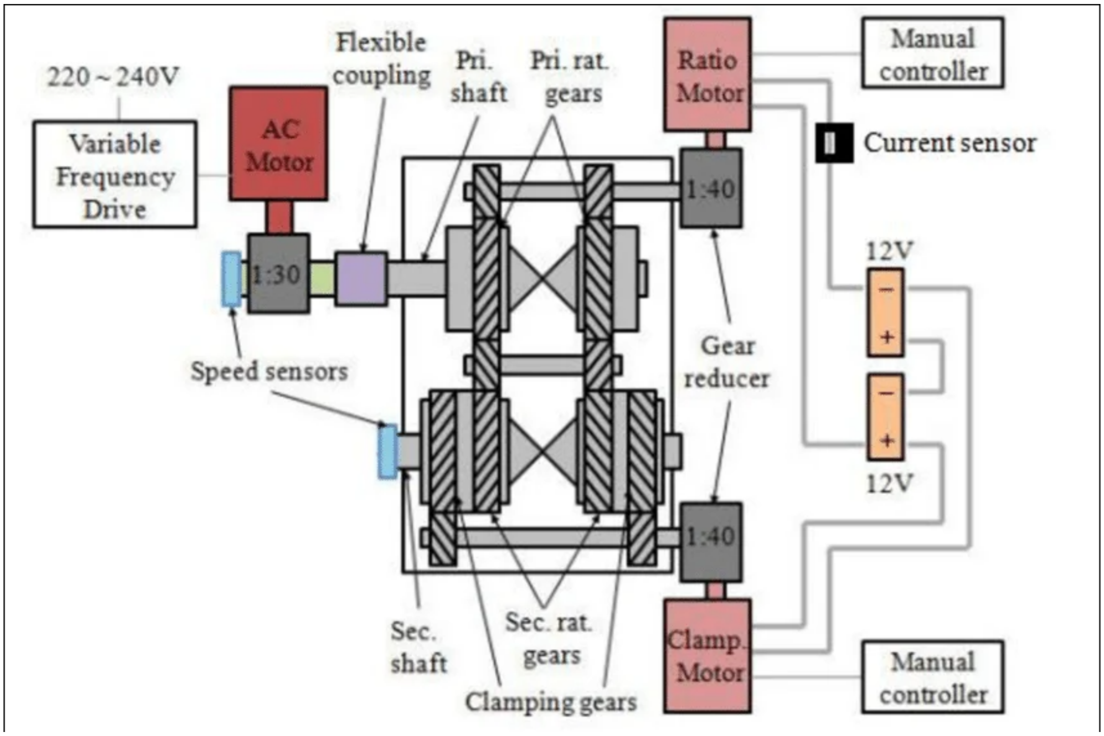

Fig. 5. Electromechanical CVT (Hybrid System).

This configuration allows flexible control of operating conditions, including decoupling engine speed from output speed. Such systems are widely used in hybrid vehicles. They are efficient. Quite efficient, actually. But they are also complex, both in terms of hardware and control algorithms.

E. Emerging CVT Technologies

In addition to established transmission types, several emerging technologies are being actively developed. These systems are still not as widely used, but they represent important directions for future research. Examples include magnetic CVTs and advanced traction drives, as indicated in Fig. 1. A conceptual representation of such systems is shown in Fig. 6.

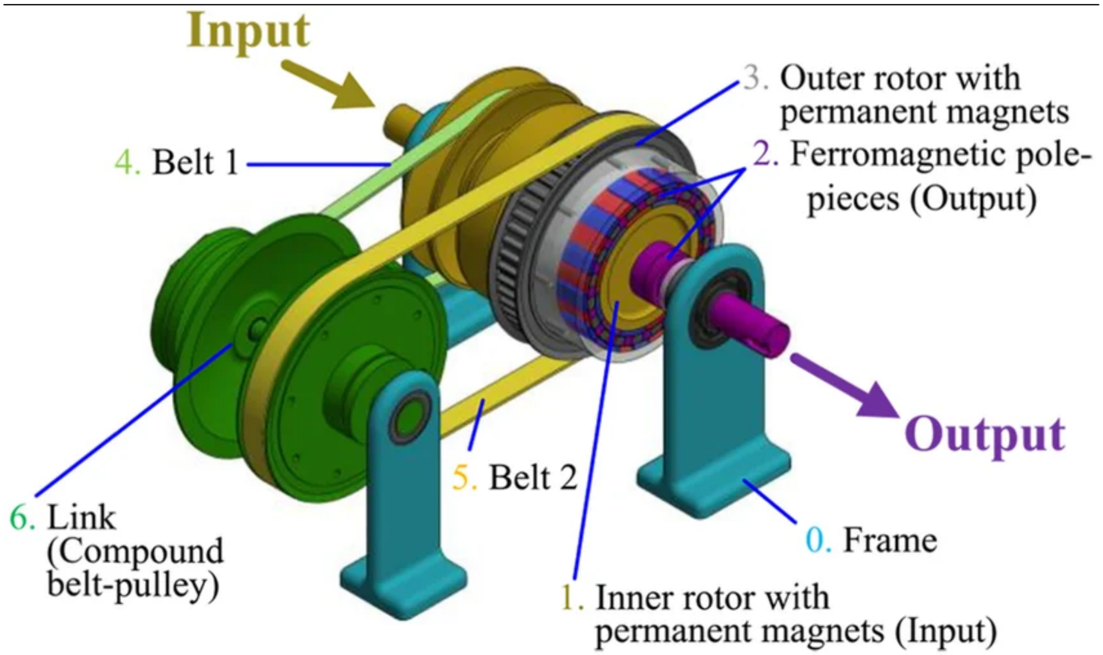

Fig. 6. Magnetic / Traction CVT.

Magnetic CVTs transmit torque without direct mechanical contact, which eliminates wear and reduces maintenance requirements. Traction drives, on the other hand, rely on special fluids that can transmit high forces under pressure through thin contact films [29,30,33]. These technologies offer interesting advantages. No wear. High efficiency potential. But also limitations — mainly related to torque capacity, cost, and technological complexity.

III. KEY PERFORMANCE PARAMETERS OF CONTINUOUSLY VARIABLE TRANSMISSIONS

In order to compare different types of continuously variable transmissions in a consistent and meaningful way, it is necessary to define a common set of performance parameters. These parameters describe the essential characteristics of CVT systems, including their kinematic behavior, power capability, efficiency, and operational features. Without such a unified framework, comparison becomes fragmented and often subjective. Therefore, the following subsections introduce the key parameters used in this study, which will serve as the basis for the subsequent analysis and comparison of different transmission types.

A. Transmission Ratio and Ratio Range

The transmission ratio is one of the fundamental parameters used to describe the operation of any transmission system. It defines the relationship between the input and output angular velocities [3]. In the case of continuously variable transmissions, this ratio can change smoothly over a certain range, without discrete steps. In general, the transmission ratio is defined as

$$i = \frac{\omega_{in}}{\omega_{out}} \tag{1}$$

where ω_{in} and ω_{out} are the angular velocities of the input and output shafts, respectively.

For CVT systems, it is not only the instantaneous value of the transmission ratio that is important, but also the range over which it can vary. This range is typically expressed as

$$R = \frac{i_{max}}{i_{min}} \tag{2}$$

where i_{max} and i_{min} represent the maximum and minimum achievable transmission ratios.

This parameter determines the flexibility of the transmission and its ability to adapt to different operating conditions. A wider ratio range allows the system to operate efficiently over a broader spectrum of speeds and loads.

At the same time, the continuity of ratio variation is a defining feature of CVTs. Unlike stepped gearboxes, where the transmission ratio changes discretely, CVTs provide a smooth transition between values. This eliminates shift shocks and allows the prime mover to operate closer to its optimal mode.

B. Torque abd Power Capacity

Torque and power capacity are key parameters that determine the ability of a transmission to operate under load. These characteristics define the maximum mechanical energy that can be transmitted without failure or excessive degradation of components [32]. Torque is typically defined as the rotational force acting on a shaft and can be expressed as

$$T = \frac{P}{\omega} \tag{3}$$

where T is the torque, P is the transmitted power, and ω is the angular velocity.

In practical systems, the maximum transmissible torque is limited by different physical factors depending on the type of CVT. In friction-based systems [10,15], the limit is mainly determined by contact forces and friction coefficients between interacting elements. If the contact force is insufficient, slipping occurs.

In hydrostatic transmissions, torque capacity is related to fluid pressure and the displacement of hydraulic machines. Higher pressure allows greater torque, but it also increases mechanical and volumetric losses.

For electromechanical systems, the limitations are associated with the power ratings of electric machines and thermal constraints. Electrical losses and heat generation become critical at high loads. Power capacity, in turn, defines the total energy transfer rate and is often a more relevant parameter for system-level analysis. While torque characterizes load-carrying ability, power determines overall performance in dynamic operating conditions.

Thus, both torque and power capacity must be considered together when evaluating and comparing different types of continuously variable transmissions.

C. Efficiency of Power Transmission

Efficiency is one of the most critical parameters in the evaluation of continuously variable transmissions [11,16]. It reflects how effectively the input power is converted into useful output power, and directly influences fuel consumption, thermal loading, and overall system performance. In general, the efficiency of a transmission can be expressed as

$$\eta = \frac{P_{out}}{P_{in}} \tag{4}$$

where P_{in} is the input power and P_{out} is the output power.

In real systems, efficiency is always less than unity due to various losses. These losses depend strongly on the transmission type. In friction-based CVTs, the main sources of losses are sliding friction, contact deformation, and internal friction within belts or chains. Even small slip can lead to noticeable efficiency reduction.

Hydrostatic transmissions experience both volumetric and mechanical losses. Leakage in hydraulic components reduces volumetric efficiency, while friction in moving parts contributes to mechanical losses. As a result, efficiency in such systems can vary significantly with operating conditions.

Electromechanical CVTs introduce additional sources of losses due to energy conversion. Mechanical energy is partially converted into electrical energy and then into mechanical form. Each conversion stage introduces losses, including electrical resistance and magnetic losses in machines.

It should also be noted that efficiency is not constant. It depends on speed, load, and operating regime. In many cases, CVTs exhibit their highest efficiency within a limited operating range. Outside this range, efficiency may decrease quite rapidly. Therefore, when comparing different CVT systems, it is important to consider not only peak efficiency values but also the overall efficiency characteristics across the entire operating range.

D. Dynamic Response and Control Characteristics

Dynamic response is an important parameter that characterizes how quickly and smoothly a transmission can adjust its operating state in response to changing conditions. In continuously variable transmissions, this mainly refers to the ability to change the transmission ratio over time. In a simplified form, the rate of change of the transmission ratio can be expressed as

$$\dot{i} = \frac{di}{dt} \tag{5}$$

where $\dot{i}$ represents the speed of ratio variation.

A higher value of $\dot{i}$ indicates a faster response of the system. This is particularly important [18,23] in applications where operating conditions change rapidly, such as in automotive systems during acceleration or deceleration.

The dynamic behavior of a CVT depends strongly on its control mechanism. In friction-based systems, ratio changes are typically achieved through mechanical or hydraulic actuators that adjust the position of pulleys or rollers. These systems can respond relatively quickly, although inertia and friction may limit their performance.

Hydrostatic transmissions exhibit different dynamic characteristics. Since the ratio is controlled by fluid flow, response time depends on the dynamics of the hydraulic system, including fluid compressibility and actuator speed. This can introduce delays, especially under varying load conditions.

Electromechanical CVTs generally offer faster and more flexible control. Electronic systems can adjust operating parameters almost instantaneously, allowing precise control of power flow. However, this also requires sophisticated control algorithms and coordination between mechanical and electrical components.

In addition to response speed, stability is another important aspect. Rapid changes in transmission ratio may lead to oscillations or control instability if not properly managed. Therefore, both response time and control stability must be considered when evaluating the dynamic performance of continuously variable transmissions.

E. Structural Characteristics (Size, Mass, and Complexity)

Structural characteristics play an important role in determining the applicability of a transmission in real systems. Even if a CVT demonstrates high efficiency or wide ratio range, its practical use may be limited by size, weight, or design complexity. The overall mass and dimensions of a transmission are directly related to its power capacity and operating principle [4,5]. Friction-based CVTs are generally compact and lightweight, which makes them suitable for passenger vehicles and small machines. In contrast, hydrostatic and hydromechanical systems tend to be larger and heavier due to the presence of pumps, motors, and additional components. One commonly used indicator is the torque-to-mass ratio, which can be expressed as

$$\gamma = \frac{T_{max}}{m} \tag{6}$$

where T_{max} is the maximum transmissible torque and mis the mass of the transmission.

This parameter allows comparison of how efficiently different systems utilize their mass to transmit torque. Higher values indicate more compact and efficient designs in terms of weight.

Another important aspect is structural complexity. Some CVTs, such as belt or chain systems, have relatively simple constructions. Others, like hydromechanical or electromechanical transmissions, involve multiple subsystems, including planetary gears, hydraulic units, or electrical machines. Increased complexity often leads to higher manufacturing cost and more demanding maintenance requirements. But at the same time, it may provide improved performance and functionality. So there is always a trade-off. Simplicity versus capability.

F. Reliability and Wear Mechanisms

Reliability is a critical factor in the evaluation of continuously variable transmissions, especially in applications where long service life and minimal maintenance are required. Different types of CVTs are subject to different wear mechanisms. In friction-based systems, wear occurs mainly at the contact surfaces between belts, chains, rollers, and pulleys. Repeated loading can lead to surface fatigue, material degradation, and eventual failure. In hydrostatic transmissions, there is no direct mechanical contact in the same sense, but reliability is affected by fluid quality, leakage, and wear of internal components such as pumps and motors [29,30]. Contamination of the working fluid can significantly reduce system lifetime. Electromechanical systems introduce additional reliability considerations related to electrical components. These include thermal stresses, insulation degradation, and electronic control failures. In general, reliability can be qualitatively described through service life and failure rate. A simplified representation of reliability over time may be expressed as

$$R(t) = e^{-\lambda t} \tag{7}$$

where $R(t)$ is the probability of failure-free operation and λ is the failure rate.

Although this expression is idealized, it highlights the importance of minimizing failure mechanisms in transmission design

G. Control and Application Aspects

Control characteristics and application range are closely related and are therefore considered together. The effectiveness of a CVT depends not only on its mechanical performance but also on how well it can be controlled under real operating conditions. Different transmission types require different control approaches. Mechanical CVTs often rely on relatively simple control systems, sometimes even purely mechanical ones. Hydrostatic systems typically use hydraulic control, which allows smooth adjustment but may introduce delays. Electromechanical CVTs require advanced electronic control systems [18,22]. These systems manage power flow between mechanical and electrical paths and must coordinate multiple components simultaneously. As a result, they offer high flexibility but also increased system complexity. The application range of CVTs is very broad. Friction-based systems are commonly used in passenger vehicles and light machinery. Hydrostatic and hydromechanical transmissions are dominant in heavy-duty applications such as agricultural and construction equipment. Electromechanical systems are widely used in hybrid vehicles and modern energy-efficient powertrains. Thus, the choice of a particular CVT type depends not only on its technical parameters but also on the specific requirements of the application, including power level, operating conditions, and control strategy.

IV. ANALYSIS OF MAJOR CVT TYPES

In this section, the main types of continuously variable transmissions are analyzed in terms of their operating principles, structural features, and key performance parameters introduced in the previous section. Each transmission type is considered separately in order to highlight its advantages, limitations, and typical areas of application. The analysis focuses on practical characteristics such as transmission ratio range, torque capacity, efficiency, dynamic response, and reliability. Particular attention is given to the relationship between the physical operating principle and the resulting performance of each system.

A. Belt and Chain CVTs

Belt and chain CVTs are the most widely used continuously variable transmissions, particularly in automotive applications [10,15]. Their operating principle is based on frictional interaction between a flexible element (belt or chain) and a pair of variable-diameter pulleys, as previously illustrated in Fig. 2. The transmission ratio is controlled by adjusting the distance between the conical pulley halves, which changes the effective radius of contact. As a result, the ratio varies continuously within a defined range. In terms of performance parameters, these systems offer a moderate ratio range, typically up to 6:1. Their efficiency is relatively high, often exceeding 85%, although it depends on operating conditions and the level of slip between contacting elements. Torque capacity is limited by the strength of the belt or chain and the allowable contact pressure. Chain CVTs generally provide higher torque capacity and improved durability compared to belt systems. However, they are also more complex and expensive. From a structural perspective, belt and chain CVTs are compact and relatively lightweight. This makes them well suited for passenger vehicles, where space and mass are critical factors. At the same time, wear remains a key issue. Continuous contact under load leads to gradual degradation of components, especially under high torque conditions. Overall, these systems represent a good compromise between simplicity, efficiency, and functionality, which explains their widespread use.

B. Toroidal and Traction-Drive CVTs

Toroidal and traction-drive CVTs operate on the principle of rolling contact with the use of traction fluids, as conceptually shown in Fig. 6. In these systems, torque is transmitted through rollers positioned between rotating disks. The transmission ratio is varied by changing the contact geometry, typically by adjusting the tilt angle of the rollers. One of the main advantages of these systems is their relatively high torque capacity compared to belt-type CVTs [29,31]. The use of traction fluids allows the transmission of significant forces through a thin contact layer under high pressure. Efficiency can also be quite high, especially when operating under optimal conditions. However, losses may increase due to slip and internal fluid behavior. From a dynamic standpoint, these systems are capable of fast ratio adjustment. The absence of flexible elements such as belts reduces certain limitations related to deformation and inertia. On the other hand, the design of toroidal CVTs is more complex. Precision manufacturing is required to ensure proper contact conditions and avoid excessive wear. Surface fatigue and lubrication quality are critical factors affecting reliability. These systems are typically used in high-performance or specialized applications, where higher torque capacity and smooth operation are required.

C. Hydrostatic Transmissions

Hydrostatic transmissions, illustrated in Fig. 3, are widely used in heavy-duty applications where precise control and high torque at low speeds are required. Their operating principle is based on the conversion of mechanical energy into hydraulic energy and vise versa. A variable-displacement pump generates fluid flow, which drives a hydraulic motor [8,20]. By adjusting the displacement, the output speed and torque can be continuously controlled. One of the key advantages of hydrostatic systems is their ability to provide an infinite transmission ratio range, including zero output speed. This makes them highly suitable for applications such as tractors and construction machinery. However, efficiency is generally lower than in mechanical CVTs. Losses occur due to fluid leakage, viscous effects, and friction within hydraulic components. These losses become more significant at higher speeds. Structurally, hydrostatic transmissions are larger and heavier than friction-based systems. They also require careful maintenance of the hydraulic fluid to ensure reliable operation. Despite these drawbacks, their robustness and controllability make them indispensable in many industrial applications.

D. Hydromechanical CVTs

Hydromechanical CVTs, shown in Fig. 4, combine mechanical and hydrostatic power transmission paths. This approach allows them to overcome some of the limitations of purely hydrostatic systems. In these transmissions, power is split into two branches: one mechanical and one hydraulic. The outputs of these branches are then recombined using a planetary gear system. By controlling the hydraulic path, the overall transmission ratio can be varied continuously. This configuration improves overall efficiency, since only part of the power passes through the less efficient hydraulic system [14,19]. At the same time, the system retains the ability to provide smooth ratio variation and high torque at low speeds. Hydromechanical CVTs are typically used in high-power applications, such as agricultural tractors. They offer a good balance between efficiency and controllability. However, their structure is significantly more complex than that of simpler CVTs. This increases cost and requires more advanced control systems.

E. Electromechanical CVTs

Electromechanical CVTs, illustrated in Fig. 5, are widely used in hybrid powertrains. These systems combine mechanical transmission with electrical energy conversion. Power from the engine is divided into two paths: a mechanical path and an electrical path. The electrical path includes a generator and an electric motor, which allows flexible redistribution of power depending on operating conditions. One of the main advantages of this approach is the ability to decouple engine speed from output speed. This allows the engine to operate in its optimal efficiency range more often. Efficiency of electromechanical CVTs can be quite high, especially when energy flows are properly managed. However, multiple energy conversion stages introduce additional losses. From a structural point of view, these systems are complex [22,25,28]. They require not only mechanical components but also electrical machines and control electronics. Nevertheless, their flexibility and compatibility with hybrid systems make them increasingly important in modern engineering.

F. Emerging CVT Technologies

Emerging CVT technologies include magnetic transmissions and advanced traction-drive systems, as indicated in Fig. 6. Magnetic CVTs transmit torque without physical contact, using magnetic fields [31,33]. This eliminates mechanical wear and reduces maintenance requirements. However, current designs are limited in terms of torque capacity. Although these technologies are not yet widely used, they represent promising directions for future development of continuously variable transmissions.

V. COMPARATIVE ANALYSIS OF CVT TECHNOLOGIES

The different types of continuously variable transmissions discussed in the previous sections exhibit significantly different characteristics [10,11,14] due to their underlying operating principles. While each system is designed to provide continuous ratio variation, their performance in terms of efficiency, torque capacity, dynamic response, and structural complexity varies considerably.

TABLE I
COMPARATIVE CHARACTERISTICS OF CONTINUOUSLY VARIABLE TRANSMISSIONS

Transmission Type	**Ratio Range**	**Max Torque / Power**	**Efficiency (%)**	**Response Time**	**Size / Mass**	**Reliability & Wear**	**Control Complexity**
V-belt CVT	0.4–2.5	up to 250–300 Nm	85–92	Fast (0.2–0.5 s)	Compact	Belt wear, pulley fatigue	Medium
Chain CVT	0.4–2.4	up to 400–450 Nm	88–94	Fast (0.2–0.4 s)	Compact	Higher durability than belt	Medium
Toroidal CVT	0.3–2.5	up to 500 Nm	85–90	Very fast (0.1–0.3 s)	Medium	Contact fatigue possible	High
Disk / Roller CVT	0.2–3.0	100–200 Nm	80–90	Very fast	Compact	Surface wear significant	Medium
Hydrostatic (HST)	$0–\infty$	> 1000 Nm	75–88	Moderate (0.3–1 s)	Large, heavy	High reliability, leakage risk	Medium
Hydromechanical CVT	$0–\infty$	> 2000 Nm	85–95	Moderate	Large	Very robust	High
Electromechanical CVT	$0–\infty$	> 3000 Nm	90–97	Fast (electronic)	Medium	High reliability	Very high
Magnetic CVT	0.5–2.0	< 200 Nm	90–96	Fast	Medium	Very high (no wear)	Medium
Advanced Traction Drives	0.3–3.0	500–1000 Nm	90–97	Very fast	Medium	Good (if lubricated)	High

To provide a clear and consistent comparison, the main characteristics of the analyzed transmission types are summarized in Table 1. This table serves as a compact representation of the key performance parameters introduced in “Key Performance Parameters of Continuously Variable Transmissions” Section and applied in “Analysis of Major CVT Types” section.

A. Transmission Ratio Range

One of the most distinctive differences between CVT types lies in their achievable transmission ratio range. Friction-based CVTs, such as belt and chain systems, typically offer a moderate ratio range, usually up to 6–8. This is sufficient for most automotive applications. However, their range is limited by geometric constraints of pulleys and contact conditions. In contrast, hydrostatic and hydromechanical transmissions can theoretically achieve an infinite ratio range, including zero output speed. This gives them a significant advantage in applications requiring precise low-speed control. Electromechanical CVTs also provide a very wide effective ratio range due to the flexibility of electrical power distribution. Thus, from the perspective of ratio flexibility, hydrostatic and power-split systems offer the highest capability.

B. *Torque and Power Capacity*

The ability to transmit torque varies strongly across different CVT types. Friction-based systems are generally limited by contact forces and material strength. While modern chain CVTs can handle relatively high torque levels, they are still constrained compared to other transmission types. Hydrostatic and hydromechanical transmissions, on the other hand, are capable of transmitting very high torque [8,14]. This is due to the use of hydraulic pressure and robust mechanical components. These systems are therefore widely used in heavy machinery. Electromechanical CVTs can also handle high power levels, but their limitations are related to the capacity of electric machines and thermal constraints. Overall, for high-torque applications, hydrostatic and hydromechanical systems are more suitable.

C. *Efficiency Comparison*

Efficiency is one of the most critical parameters in the evaluation of CVTs. However, it is also one of the most variable. Friction-based CVTs typically achieve efficiencies in the range of 85–92%, depending on operating conditions. Chain systems tend to perform slightly better than belt systems due to reduced slip. Hydrostatic transmissions generally have lower efficiency, often in the range of 75–85%, mainly due to fluid losses [11,16]. Hydromechanical CVTs improve upon this by reducing the proportion of power transmitted through the hydraulic path, achieving efficiencies up to 90–95%. Electromechanical systems can reach high efficiency levels as well, especially when operating near optimal conditions. However, multiple energy conversion stages introduce additional losses. Thus, the highest efficiency is typically observed in mechanical and power-split systems, while purely hydrostatic systems are less efficient.

D. *Dynamic Response and Control*

Dynamic response varies depending on the control mechanism of the transmission. Friction-based CVTs generally provide relatively fast response, as the ratio is adjusted through mechanical or hydraulic actuators. Hydrostatic systems may exhibit slower response due to fluid dynamics and actuator limitations. However, they offer very smooth control. Electromechanical CVTs provide the highest level of control flexibility. Electronic systems allow rapid adjustment of operating conditions and precise power management. Hydromechanical systems fall somewhere in between, combining hydraulic control with mechanical response characteristics.

E. *Structural Complexity and Reliability*

There is a clear trade-off between simplicity and functionality. Friction-based CVTs are relatively simple in design and compact in size. This makes them cost-effective and widely used. However, they are subject to wear at contact surfaces. Hydrostatic systems are more robust but require additional components such as pumps and hydraulic circuits. Maintenance of fluid quality is critical for reliability. Hydromechanical and electromechanical CVTs are significantly more complex. They involve multiple subsystems and require advanced control strategies. While they offer improved performance, this comes at the cost of increased system complexity and higher production cost. Emerging technologies, such as magnetic CVTs, offer potential advantages in terms of reduced wear, but are not yet mature enough for widespread use.

F. Application Suitability

Each CVT type is best suited for specific applications [19,25].

Friction-based CVTs dominate in passenger vehicles and light machinery

- Friction-based CVTs dominate in passenger vehicles and light machinery
- Hydrostatic systems are widely used in heavy equipment
- Hydromechanical transmissions are preferred in high-power agricultural machinery
- Electromechanical CVTs are essential in hybrid and electrified powertrains

This distribution reflects the balance between efficiency, torque capacity, and control requirements in different fields.

VI. CONCLUSIONS

This paper presented a structured overview and comparative analysis of the main types of continuously variable transmissions based on their operating principles and key performance parameters. A unified classification of CVTs was proposed, including friction-based mechanical systems, hydrostatic and hydromechanical transmissions, electromechanical power-split systems, and emerging technologies. The analysis showed that different transmission types exhibit significantly different characteristics depending on their physical principles. Friction-based CVTs offer a good balance between simplicity, compactness, and efficiency, which explains their widespread use in automotive applications. However, their torque capacity is limited by contact conditions and material constraints. Hydrostatic transmissions provide excellent controllability and the ability to achieve zero output speed, making them highly suitable for heavy machinery. At the same time, their efficiency is lower due to hydraulic losses. Hydromechanical CVTs improve this limitation by combining mechanical and hydraulic power paths, resulting in higher overall efficiency while maintaining good controllability. Electromechanical CVTs demonstrate high flexibility and efficiency, especially in hybrid powertrains, where electrical energy conversion allows optimal operating conditions of the prime mover. However, these systems are characterized by high structural and control complexity. Emerging technologies, such as magnetic and advanced traction-drive CVTs, show promising potential due to reduced wear and high efficiency. Nevertheless, their practical application is currently limited by technological and economic constraints. The comparative analysis summarized in Table 1 confirms that no single CVT type can be considered universally optimal. The selection of a transmission system must be based on specific application requirements, including power level, efficiency, controllability, and system complexity. Future research should focus on improving efficiency across wider operating ranges, reducing system complexity, and developing new materials and technologies that enhance durability and performance. Particular attention should be given to hybrid and electrified transmission systems, which are expected to play a key role in the development of modern energy-efficient machines [25].

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