2013 21st Mediterranean Conference on Control & Automation (MED)
Platanias-Chania, Crete, Greece, June 25-28, 2013

On the Efficiency of a Prototype Continuous Variable Transmission System

P. Spanoudakis, N. C. Tsourveloudis

***Abstract*— In this paper we explore the performance capabilities of a new variable transmission system installed on a low fuel consumption, zero emission, prototype urban vehicle. Our focus is on measuring the efficiency of the continuous variable transmission system, namely, the Electronic Shift Variable Transmission (ESVT), which is presented here in a lightweight conceptually simple design as part of the powertrain of a hydrogen fuel cell powered urban vehicle, developed at the Technical University of Crete. To evaluate ESVT's operational ability, a laboratory testbed was developed, mainly to imitate full scale driving conditions in terms of power needs for various external loads. Testbed's configuration and experimental measurements are presented, providing insight on technical characteristics and limitations of the proposed prototype transmission.**

***Keywords*— CVT, efficiency, powertrain**

I. Introduction

The Continuously Variable Transmission (CVT) system was firstly conceptualized by Leonardo Da Vinci in 1490 and installed on a vehicle for the first time in 1910, by Zenith motorcycle manufacturer [1]. Although CVTs have been used in automobiles for decades, limited torque capabilities and questionable reliability have inhibited their growth [18]. Nowadays, CVTs are aggressively competing with automatic transmissions and several vehicle manufacturers, are already keen on exploiting the various advantages of a CVT in a production vehicle [1, 2].

Theoretically, a Continuous Variable Transmission (CVT) has an infinite number of transmission ratios, which can be achieved without the driver's intervention, as in automatic transmissions. The technological advantage is that CVTs change gear ratios at every time instant so as to achieve optimal engine efficiency. This improves the mileage compared to traditional (manual or automatic) gear boxes by allowing better matching of the engine operating conditions to the variable driving scenarios.

Several different types of CVTs have been developed through the years, each having their own characteristics. The most referenced types found are: Spherical CVT [4], Hydrostatic CVT [5, 6], E-CVT [7, 8], Toroidal CVT [9–11], Power-split CVT [12–14], Belt CVT [17], Chain CVT [17], Ball-type toroidal CVT [15], and Milner CVT [16]. However, belt and chain types are the most commonly used CVTs, among all, in automotive applications.

In general, transmission efficiency is crucial for the energy consumption of a vehicle. Manual and automatic transmissions are the most commonly used on cars until now, presenting high efficiencies. Specifically, the efficiency of Manual Transmissions (MTs) ranges from 96.2% and may be improved up to 96.7% the most. Concerning the overall efficiency of Automatic Transmissions (ATs), it is found to be around 85.3%, whereas the efficiency of the best current AT could be improved up to 86.3% [3, 18]. At the same time, the overall efficiency of belt type CVTs is estimated at 84.6%, and may be improved towards 88.4% by reducing hydraulic pump losses These losses practically determine the efficiency of CVTs and of ATs, and they are relatively high at low transmission loads. The improvement of pump and hydraulic circuit design can substantially increase the efficiency of CVT and AT and it is a subject of ongoing research [3, 18]. Alternatively, the actuation of the clutches and of the CVT may be (partly) electrical, so as the hydraulic losses to be replaced by potentially lower electrical losses. In the overall efficiency of toroidal or traction drive CVTs is estimated at around 91%, which may become higher by 1.8% by employing more advanced traction fluids [18, 19].

In this paper the efficiency of a new prototype CVT is researched. The proposed *Electronic Shift Variable Transmission* (ESVT), was designed and implemented at the Technical University of Crete, in order to be installed on the ER12 prototype hydrogen (H_2) fuel cell powered urban vehicle [25]. The main reason to use a CVT was to achieve lower energy consumption by operating the vehicle's electric motor at its optimal efficiency region. At the same time, low weight and simple construction were targeted for the specific application. In order to explore ESVT efficiency, a testbed was developed and experimental measurements were conducted and are presented hereafter. ESVT power transfer capability is also considered and therefore different experiments are conducted to examine flat belt type suitability for the specific application. The use of a flat belt, instead of the common V-belts used mostly on existing CVT's, is the main reason for these additional tests, providing more insight on this proposed technology. To the best of our knowledge, no similar system has been developed and evaluated on electric vehicles so far.

P. Spanoudakis is with the Department of Production Engineering and Management, Technical University of Crete, Chania, 73100 Greece, (e-mail: hroniss@dpem.tuc.gr).

N. C. Tsourveloudis is with the Department of Production Engineering and Management, Technical University of Crete, Chania, 73100 Greece, (corresponding author to provide phone: +302821037285; fax: +302821069410; e-mail: nikost@dpem.tuc.gr)

II. The Prototype Electronic Shift Variable Transmission

The proposed Electronic Shift Variable Transmission (ESVT) consists of a) mechanical components which transmit the power from an electric motor to the wheel and b) electronics, which are responsible for gear ratio change and control. A description of these components regarding ESVT operation and control follows.

A. Mechanical Structure

An assembly of the main mechanical parts for the proposed ESVT, is shown in Fig. 1. As shown, the power is transfered by two cone pulleys that are connected through a flat belt. Power input is provided by a motor (electric motor in the case presented here) to the lower cone pulley and it is transmitted to the upper cone pulley using the flat belt. Power output is provided to the wheel for vehicle movement. The movement of the belt along the pulleys provides the shifting of gears (i.e. change of gear ratio), which results to theoretically infinite variable ratio transmission. A linear actuator, driven by a controller, handles belt movement along the pulleys. A schematic diagram of the ESVT main components when it is installed on a vehicle is shown in Fig. 2.

The transmission system described here was designed and built in order to provide certain capabilities to a specific prototype vehicle, whose objective is the lowest possible fuel consumption.

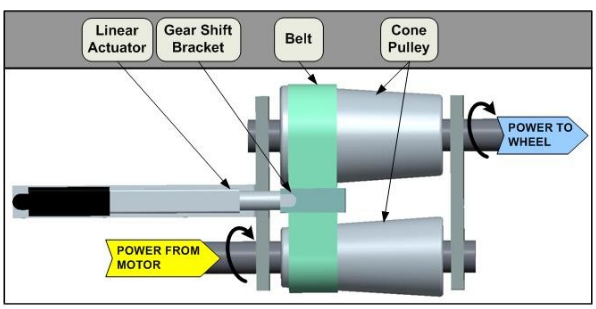

Figure 1. The ESVT main mechanical parts assembly.

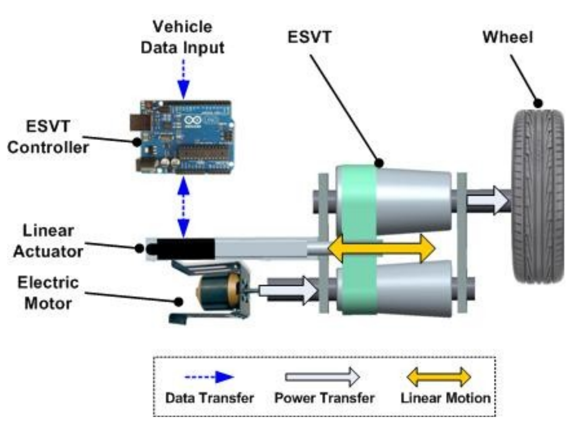

Figure 2. Schematic diagram of the ESVT components.

The desired capabilities correspond to higher traction force thus lower consumption at vehicle launch and electronically shifted gear ratio at higher speeds, targeting electric motor best efficiency region. These targets are reached using variable gear ratios ranging from 1.5 to 1 (by the ESVT), which in addition to a fixed secondary gear results to a final drive of 1:15 to 1:10. The secontary gearing is used to raise the torque at the levels needed to move the specific vehicle. In particular, the proposed ESVT transmission transfers up to 2Nm of torque output (according to motor maximum power), while using the secondary gearing this is raised to 20Nm to the wheel. Nevertheless, experimental results indicate that power transfer capability can be much higher.

B. Electronics

ESVT electronics are responsible for the control of the variable gear ratio change, which from now on will be referred as electronic shift. The control system consists of:

1. **Controller.** A programmable Arduino microcontroller is used, where *throttle*, vehicle's *velocity* and *gear ratio* at every time instant are the inputs while the *new gear ratio* is extracted as output. According to input info, the new gear ratio (which corresponds to new linear actuator position) is calculated in order to change ESVT gear ratio. Electronic shift is acquired targeting best motor efficiency Rpm, and it will not discussed in detail in this paper.

2. **Linear Actuator.** A Firgelli L16 linear actuator is used to move the belt to a new position, according to controller output, which results to change of ESVT gear ratio.

III. Measuring Efficiency and Power Loss

Efficiency (n_t) of the transmission of a vehicle is defined as the power output (P_{out}) provided to the wheels divided by the power input of the electric motor (P_{input}) [3, 20]. In the following equation (1), efficiency is given as a percentage:

$$n_t = \frac{P_{out}}{P_{input}} x \quad (1)$$

At the same time, the power loss P_{loss} in a transmission is the difference between the input and the output power

$$P_{loss} = P_{input} - P_{out} > 0 \quad (2)$$

In (2) the input and output power is

$$P_{input} = T_{in}\omega_{in} \quad (3a)$$

$$P_{out} = T_{out}\omega_{out}, \quad (3b)$$

where T_{in}, T_{out}, are torque input and output, and ω_{in}, ω_{out}, are velocity input and output respectively.

In belt drive transmissions, the power loss $P_{loss,}$ can be divided into *speed loss* and *torque loss*. Nevertheless, torque loss becomes the most important factor of power loss and is mostly accounted in modeling and simulation experiments. Table I presents several loss mechanisms of belt drives that are associated to torque and speed loss, according to the relevant bibliography [20, 22].

As already mentioned, the proposed ESVT transmission uses a flat belt. In general, flat belts are more efficient than V-belts, reaching over 98% maximum efficiency and provide better performance on light loads. This is due to lower power losses during operation that correspond to [21, 22]:

1. Lower hysteresis losses at the same load, since they are thinner.
2. Less friction losses because they do not have wedging into and out of the grooves as V-belts.
3. Do not stretch with age and keep constant tension for much longer time, thus avoid slippage losses and don't need regular maintenance.

In the literature [22-24], the most popular way to present and evaluate efficiency measurements of a transmission, are the graphical representations of efficiency (%) to torque and efficiency to motor rpm. This is what we adopt in the next section, where thru these graphically represented results we provide the efficiency range of the transmission system.

IV. The Testbed

A. Testbed Main Components

In order to evaluate ESVT's operation, a testbed was developed to provide efficiency measurements in various motor RPM and external loads (torque needs). The testbed was fully designed and constructed at the Machine Tools Laboratory of the Technical University of Crete and its main components shown at Fig. 3, are: a) a rotary torque transducer (DATUM M420) used to measure motor's speed (rpm), Torque (Nm) and Power (Kw), b) a hydraulic disc brake from which external loads are applied, c) a brake handle, which serves as a torque regulator, d) a brushless electric motor providing the input torque, e) an electric motor throttle adjustment for motor speed calibration and f) a laptop for data recording.

B. Experimental Setup

Numerous experiments are conducted at different motor rotation velocities (rpm) and external loads (output torque). Input and output torque at ESVT input and output respectively, are recorded at every test case, whereas efficiency is calculated according to (1).

For every efficiency calculation the following procedure is used through the tests. The rotary torque transducer is firstly placed between the electric motor and ESVT input, measuring the input torque and rpm. Then, electric motor throttle is increased to the required rpm and input torque measurement is recorded at the PC. According to electric motor specifications, max motor speed is *3500rpm*, while maximum torque is *2.0Nm*. At the same time, best motor efficiency, which is targeted for ESVT use, is reached at *2500rpm*. Thus, motor speed measurements are recorded for 500, 1000, 2000 and 2500*rpm* and torque measurements are obtained for 0.5, 1.0 and 2.0*Nm*. The maximum values, were chosen with respect to motor efficiency rpm and maximum torque, respectively.

When all input torque experiments are finalized, then the torque transducer is removed and re-installed at ESVT output, between the ESVT and the hydraulic disc brake. Experiments are repeated at exactly the same way. Thus, ESVT output torque and rpm are measured at the same conditions and according to previous input measurements, the efficiency is finally calculated for every test case.

TABLE I. Loss Mechanisms of Belt Drives [22]

Power loss of belt drives	Loss Mechanisms
Torque Loss	*Belt hysteresis*
	Friction from radial motion
	Wedge in/out
	Compression of belt
Speed Loss	*Creep*
	Rubber compliance
	Shear deflection
	Seating / unseating

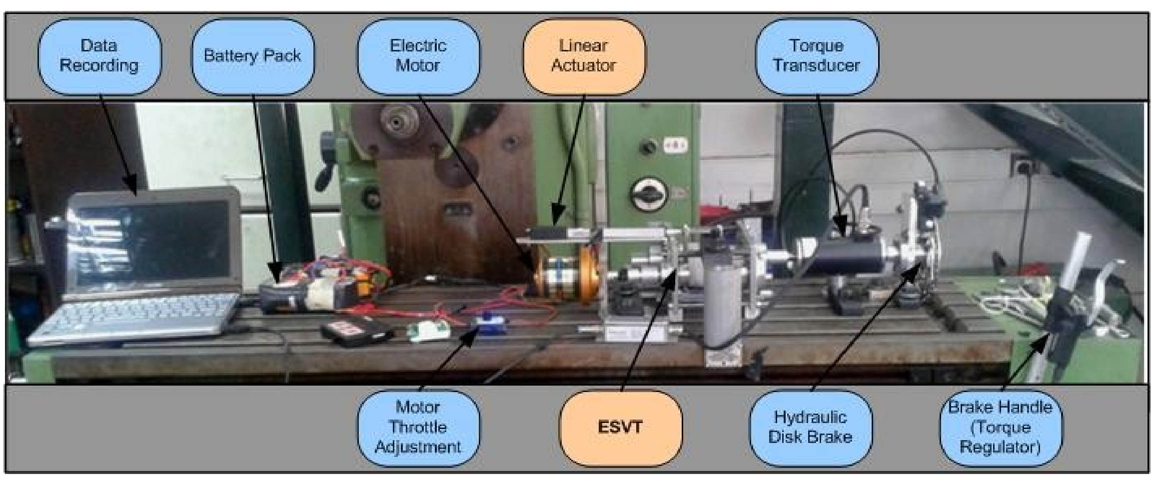

Figure 3. The testbed developed for ESVT's efficiency measurements.

As only one torque transducer is used and re-installation is required in order to measure ESVT input and output (torque and rpm), it is crucial to achieve the same conditions for every measurement. Key factors towards that target are: a) the external load adjustment, b) the throttle increase and c) the belt tension. Specifically, to provide different but standard external loads, the regulator on the brake handle (Fig. 5) is adjusted according to torque transducer readings when the torque transducer is placed at the ESVT input. When the required torque is reached, the ESVT input torque is recorded for all the needed motor rpm input. For that specific external load, the torque transducer is then re-installed at ESVT output and measurements are recorded, corresponding to ESVT output torque. Even though this procedure is time consuming, it ensures that the external load is exactly the same at both input and output measurements. For the second factor, the electric motor controller interface is set to increase the motor speed at a constant rate up to a specific rpm. In this way, throttle increase and motor rpm input, are accurate and constant for every ESVT input or output measurement, since they are adjusted directly from the motor and not according to transducer readings, that change due to ESVT transmission ratio. Finally, ESVT belt tension is pre-adjusted by two regulators which remain unchanged, avoiding any tension variations that would lead to wrong results. The belt tension regulators along with other ESVT main components, as installed on the prototype ER12 vehicle, is shown in Fig. 4.

It should also be mentioned, that temperature effects are not taken into account throughout the tests. This was decided, as after every input torque measurement, the torque transducer was re-installed and during that time room temperature was again restored at the belt and at the disc brake.

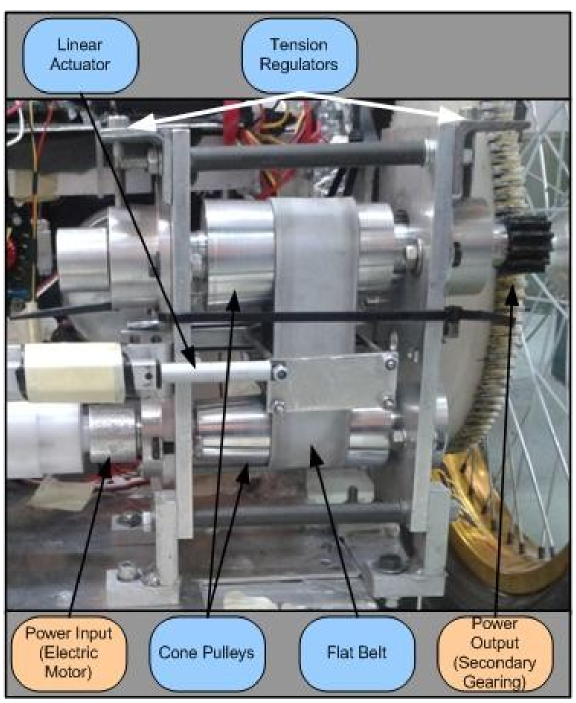

Figure 4. Main components of prototype ESVT installed on the ER12.

Finally, just one type of flat belt is used for all experiments. That belt was chosen as the most suitable for the specific application, according to its technical characteristics, but also according to experiments conducted compared to other flat belt types. These experimental results are also described in the following section.

V. RESULTS

Following the experimental setup procedure, ESVT efficiency is calculated and presented for different motor RPM and external loads. In order to proceed to these tests, a first comparison among the possible applicable flat belts is conducted and the most suitable one is chosen.

The main purpose of ESVT efficiency results is to evaluate the proposed transmission development. That means, to explore if the efficiency calculated, is close to most existing variable transmissions efficiency levels (85%), as reported in the literature and mentioned at the introduction. This first step, will then allow ESVT application to a prototype electric vehicle as the ER12, providing additional ability towards lower hydrogen consumption.

A. Flat Belt Type Comparison

On every system using a belt to transmit power, a major influence on final operational ability and efficiency is provided by the type of belt used. Thus, one important step before experimental measurements was to choose a flat belt capable to transmit the needed power that will be applied during vehicle operation. According to belt manufacturers recommendations and technical characteristics [26], four flat belts of different materials and widths where tested. The main target was to measure which one transmits the highest possible torque, hence is the most suitable for the specific ESVT application. Table II presents the technical characteristics for each type of flat belt used. All belts are from the same manufacturer (*Forbo Movement Systems*) and specifically *Extremultus P line* range. Every belt is composed by three layers corresponding to different materials, where: 1) *Top coating* (layer 1) is chrome-leather, highly wear-resistant elastomer or polyamide fabric, 2) *Tension member* (layer 2) is highly-orientated polyamide sheet and 3) *Friction coating* (layer 3) is chrome-leather or highly wear-resistant elastomer. The first two belt types, coded *GG*, have an elastomer friction layer on both sides, for power transmission on both sides, while the other two, coded *GT*, have an elastomer friction coating on one side, for power transmission on one side and top coating is made of polyamide fabric. Also, different belt widths are used for every type, as a key factor of belt power transfer.

The tests were conducted statically, using a torque wrench (BETA 606/6) ranging from 8-60Nm. The torque wrench was placed at the input of the ESVT while the output was kept firmly on a clamping device. For the same belt tension, the torque wrench adjustment was increased until the belt started to slip on the ESVT cone pulleys. This measurement was recorder as the maximum torque transferred by the specific belt type. Fig. 5, shows the maximum torque reached corresponding to each of the belt types presented at Table II.

TABLE II. TECHNICAL CHARACTERISTICS OF TESTED FLAT BELTS

Belt No.	Type	Width (mm)	Total Thickness (mm)
1	GG4P	40	2.0
2	GG4P	20	2.0
3	GT6P	25	1.3
4	GT6P	50	1.3

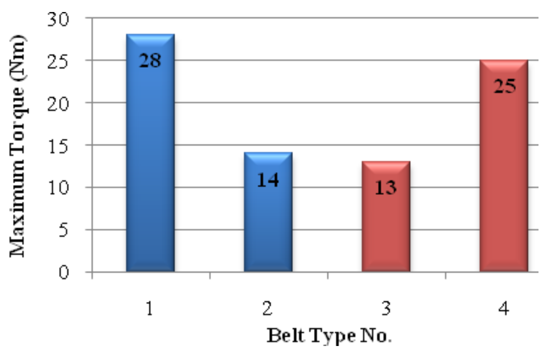

Figure 5. Maximum transferred torque for different flat belt types.

As shown, differences on coating materials of the belts provide the main torque variations. Specifically, even though belts No. 3 and 4 have larger widths which correspond to higher nominal effective pull force, they present lower torque transfer capabilities. Experimental results present maximum torque capabilities ranging from 13 to 28 Nm which all exceed maximum motor torque (2.0 Nm). According to these results, the No.1 flat belt is chosen as the most suitable for ESVT application. It is also evident from these experiments, that the proposed ESVT can be used for larger external load transfer and thus more applications.

These experiments were conducted in order to easily identify the best belt choice for the proposed transmission. If the exact belt operational characteristics in various motor rotation velocities were examined, measurements should be conducted at the efficiency testbed for every belt type. Nevertheless, this is beyond the scope of this paper.

B. *Efficiency Measurements*

As already mentioned at the experimental setup section, measurements are taken according to electric motor maximum torque and best efficiency speed (2500rpm). This is chosen, since ESVT is developed targeting a specific electric vehicle application (ER12), which in order to achieve minimum fuel consumption, it must operate closely to electric motor efficiency point and transfer more than the maximum torque.

The results obtained from the efficiency testbed, are gathered in two main figures. At Fig. 6, efficiency versus external load is presented, for different motor rpm, while at Fig. 7, efficiency versus motor rpm is shown, for different external loads.

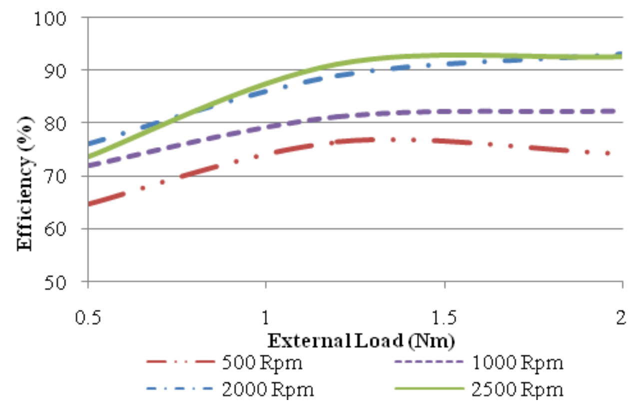

Figure 6. ESVT experimental efficiency at different external loads.

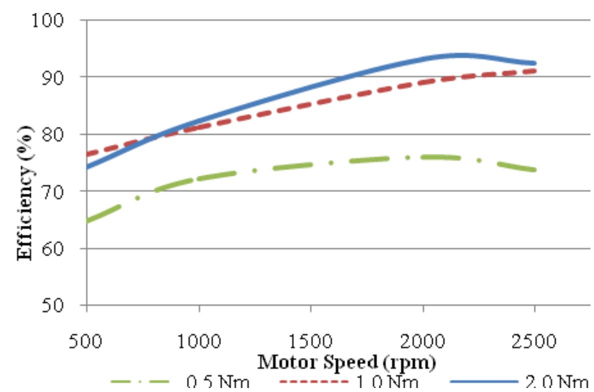

Figure 7. ESVT experimental efficiency at different motor speeds (rpm).

Experimental results show that ESVT efficiency ranges from a minimum of 70% to a maximum of 93%. As expected, best efficiency is found at higher motor speeds (2500rpm), while according to torque measurements, medium external loads provide better efficiency through all rpm range. Reversely, low efficiency results are found for high and low external loads. At low speeds, efficiency is 70-75%, while for higher speeds it raises up to 80-90%. It should be noticed, that for torques between 1.0-2.0Nm and high motor speeds (>2000 rpm), ESVT can transfer power at very good efficiencies corresponding to 87-93%. This best efficiency region, corresponds to vehicle speeds of 15-25Km/h where is mostly operated during a race. Thus, it can prove to be of major importance towards low energy consumption improvement.

It is clear that ESVT use at low motor speeds shows power losses that must be compensated by high gear ratios in order to achieve low energy consumption on a vehicle. At the same time, closely to motor best efficiency rpm, ESVT provides high efficiency levels for a wide torque range, which can for sure extend vehicle autonomy. These results also prove, that compared to most existing CVT types, the proposed ESVT provides good operational characteristics and high efficiency performance.

VI. CONCLUSION

A new Electronic Shift Variable Transmission (ESVT) was designed, developed and constructed, in order to explore the performance of variable transmission use on zero emission urban vehicles. At first, the influence of the type of belt used was tested, comparing four flat belts of different materials and widths. The main target was to choose the most suitable for the specific ESVT application. These experiments showed that the proposed ESVT can transfer higher external loads than expected and thus extend its use to more applications. Also, to evaluate ESVT operational ability, a testbed was developed in order to measure its efficiency under different electric motor rpm and external loads. Testbed configuration and experimental measurements are presented, proving that compared to most existing CVT types, the proposed ESVT provides good operational characteristics and high efficiency performance. Moreover, at motor best efficiency rpm, ESVT provides high efficiency levels for a wide torque range, which can for sure extend vehicle autonomy. At low motor speeds power losses are higher, and must be compensated by high gear ratios in order to achieve low energy consumption.

Acknowledgment

Many thanks to D. Efstathiou and J. Stratigos, both members of the TUC Eco Racing team, for their support on the physical implementation of the experimental testbed.

References

[1] S. Birch, "Audi takes CVT from 15th century to 21st century", *Automotive Engineering International online*, SAE International 2000.

[2] J. Yamaguchi, "Nissan's Extroid CVT", *Automotive Engineering International online*, SAE International, 2000.

[3] Vroemen, B., "Component control for the zero inertia powertrain", Ph.D. dissertation, Technische Universiteit Eindhoven, 2001.

[4] J. Kim, F.C. Park, Y. Park, M. Shizuo, "Design and analysis of a spherical continuously variable transmission", *ASME Journal of Mechanical Design*, vol. 124 (1), pp. 21–29, 2002.

[5] T. Iino, A. Okuda, M. Takano, M. Tanaka, K. Sakai, T. Asano, K. Fushimi, "Research of hydrostatic CVT for passenger vehicles", *JSAE Review*, vol.24 (3), pp. 227–230, 2003.

[6] P. Kanphet, P. Jirawattana, B. Direcksataporn, "Optimal operation and control of a hydrostatic CVT powertrain", *SAE Transactions Journal of Passenger Cars: Mechanical Systems*, vol. 114 (6), pp. 1838–1845, 2005.

[7] Y. Sakai, "The ''Ecvt" electro continuously variable transmission", *SAE Special Publication Papers (PT-125)*, SAE International, 1988.

[8] J.M. Miller, "Hybrid electric vehicle propulsion system architectures of the e-CVT type", *IEEE Transactions on Power Electronics*, vol. 21 (3), pp. 756–767, 2006.

[9] R. Fuchs, Y. Hasuda, I. James, "Modeling simulation and validation for the control development of a full-toroidal IVT", *Proceedings of CVT 2002 Congress*, vol. 1709, VDI Berichte, pp. 121–129, 2002.

[10] H. Tanaka, "Torque control of a double cavity half-toroidal CVT", *International Journal of Vehicle Design*, vol. 32 (3–4), pp. 208–215, 2003.

[11] S. Akehurst, D.A. Parker, S. Schaff, "CVT rolling traction drives – a review of research into their design, functionality, and modeling", *ASME Journal of Mechanical Design*, vol. 128 (5), pp. 1165–1176, 2006.

[12] V.H. Mucino, Z. Lu, J.E. Smith, B. Cowan, M. Kmicikiewicz, "Design of continuously variable power split transmission for automotive applications", *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol.215 (4), pp. 469–478, 2001.

[13] G. Mantriota, "Theoretical and experimental study of power split continuously variable transmission system: Part I", *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol.215 (7), pp. 837–850, 2001.

[14] G. Mantriota, "Fuel consumption of a vehicle with power split CVT system", *International Journal of Vehicle Design*, vol.37 (4), pp. 327–342, 2005.

[15] N.P. Belfiore, G. De Stefani, "Ball toroidal CVT: a feasibility study based on topology, kinematics, statics and lubrication", *International Journal of Vehicle Design*, vol.23 (3–4), pp. 304–331, 2003.

[16] P.J. Milner, "CVT for high torque applications", *Proceedings of CVT 2002 Congress*, vol. 1709, VDI Berichte, pp. 543–554, 2002.

[17] Nilabh Srivastava, Imtiaz Haque, "A review on belt and chain continuously variable transmissions (CVT): Dynamics and control", *Mechanism and Machine Theory*, vol.44, pp.19–41, 2009.

[18] Kluger, M. A. and Long, D. M. "An overview of current automatic, manual and continuously variable transmission efficiencies and their projected future improvements". *SAE Technical Paper Series*, no.1999-01-1259, 1999.

[19] Machida, H. "Traction drive CVT up to date", *Proc. of the Intern. Congress on Continuously Variable Power Transmission (CVT'99)*, pp. 71–769, 1999.

[20] Almeida A., Greenberg S., "Technology assessment: energy-efficient belt transmissions", *Journal of Energy and Buildings*, vol. 22, pp.245-253, 1995.

[21] Moff R., "Flat belts", *Machine Design*, pp.52-70, 1989.

[22] Chen T.F., Lee D.W., Sung C.K., "An experimental study on transmission efficiency of a rubber v-belt CVT", *Mech. Mach. Theory*, vol. 33 (4), pp.351-363, 1998.

[23] C. Zhu, H. Liu, J. Tian, Q. Xiao, X. Du, "Experimental Investigation on the efficiency of the Pulley-Drive CVT", *International Journal of Automotive Technology*, vol. 11 (2), pp. 257−261, 2010.

[24] Sheldon S. Williamson, Srdjan M. Lukic, Ali Emadi, "Comprehensive Drive Train Efficiency Analysis of Hybrid Electric and Fuel Cell Vehicles Based on Motor-Controller Efficiency Modeling", *IEEE Transactions on Power Electronics*, vol. 21(3), 2006.

[25] Tuc Eco Racing team internet site, www.tucer.tuc.gr.

[26] Forbo Movement Systems, Product Range – Power Transmission Belts, 2012.