Power-split transmissions for construction machinery

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Abstract

Actual requirements and future challenges of travel drives are demonstrated based on wheel loader applications. Potential to raise productivity, to improve efficiency and automation versus established hydrodynamic and hydrostatic travel drives will be shown.

Dana Rexroth Transmission Systems – a Joint Venture of Bosch Rexroth AG and Dana Holding Corp. – offers a new hydro-mechanical variable power-split transmission (HVT) for construction machinery. Design and functionality of the HVT and applied development methods for endurance dimensioning and model based software design are presented. Potential of the transmissions tractive-, ratio- and power-management capabilities will be demonstrated with measured values. For this, results from drive and working operations on a 4-wheel-drive roller test bench and field operation will be presented.

KEYWORDS: power-split transmissions, efficiency, mobile applications

1 Introduction − loader transmission technology

Hydrostatic transmissions are established in wheel and track loader applications [1] below 12t operation weight. In heavier machines, hydrostatic power-shift and summation technologies [2] are competing with hydrodynamic power-shift transmissions. Hydrostatic summation solutions provide efficiency benefits (especially in operations at lower operational speeds), advanced automation functionality and power management strategies with optimized diesel engine operations. But they still have a high potential to increase efficiency at higher operational speeds.

Power-split CVT transmission technology [3] provides a clear step of improvement with efficiencies above torque converters and hydrostatic transmissions [4]. They are economic solutions to manage future challenges for wheel loader transmissions such as reduction of emissions and wear, while increasing efficiency, productivity and robustness. The hydro-mechanical variable transmission (HVT) has been presented at Bauma in 2010 [5] and is one of first products expected to be established in high-technology wheel loaders. This paper describes the HVT development and the transmission technology for construction machines.

2 Requirements for wheel loader transmissions

Wheel loader operations

Figure 1 provides typical speed and load requirements for a wheel loader operating in short and long load cycles. Long load cycles are characterized by accelerations up to maximum speeds (approx. 20..25 kph) which are possible on the specific road layouts and surface conditions. Depending on the transmission technology, suitable deceleration may be achieved with decoupling and coasting against the roller resistance of wheels and axles.

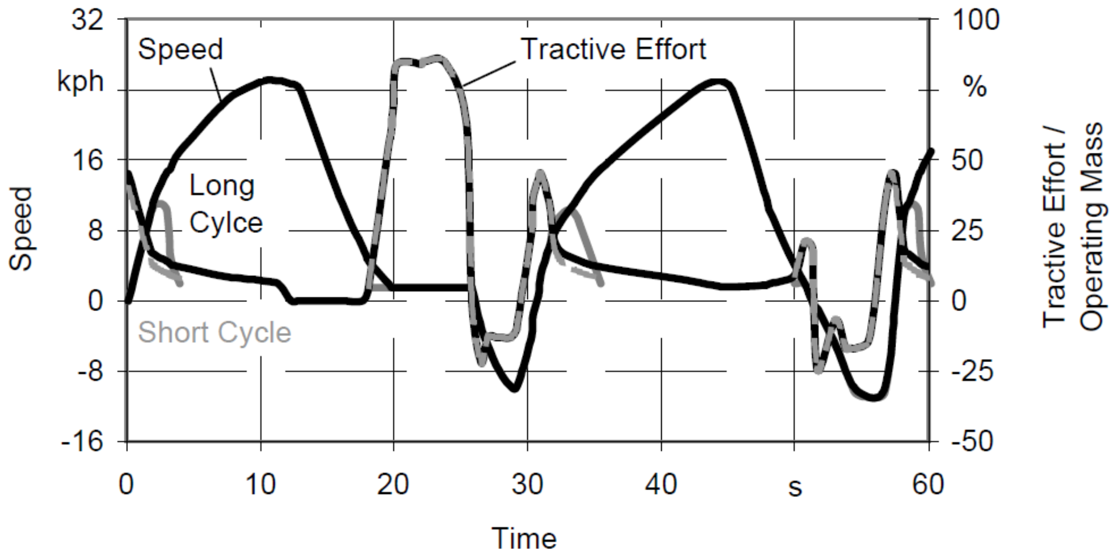


Figure 1: Speed and tractive effort in long and short load cycles

The loading operations are introduced with high dynamic ratio decrease and tractive effort rise up to levels of 60..90% of the machine weight. Torque control management and a balance of tractive effort level and feed rate is a very important function to load the bucket productively. These loading and digging operations are mostly performed at speeds below 5 kph.

Once the bucket is filled, the wheel loader is accelerating backwards, reversing and then returning to the port of discharge. After deceleration, the loader is climbing up a small ramp to discharge. Comfortable positioning under changing load conditions and the capability for suitable power share of travel drive and implement hydraulics are important to provide productive performance. Short load cycles have comparable requirements with lower maximum speeds. The shortest truck loading cycle has a maximum speed of approximately 8..10 kph.

CVT transmission load and speed spectrum

Figure 2 shows the expected tractive effort and speed spectrum for CVT wheel loaders above 20 t operational weight or 14 t tipping load in a representative mixture of typical operations like:

- short (truck loading) and long load-cycles, crusher charging, face/bank digging
- loading of different material on different grounds
- stockpiling, dozing, soil/material stripping
- transportation on level and steep roads, including off-road conditions

It is important to mention that especially in heavy machines also single operation usage occurs to a certain extent.

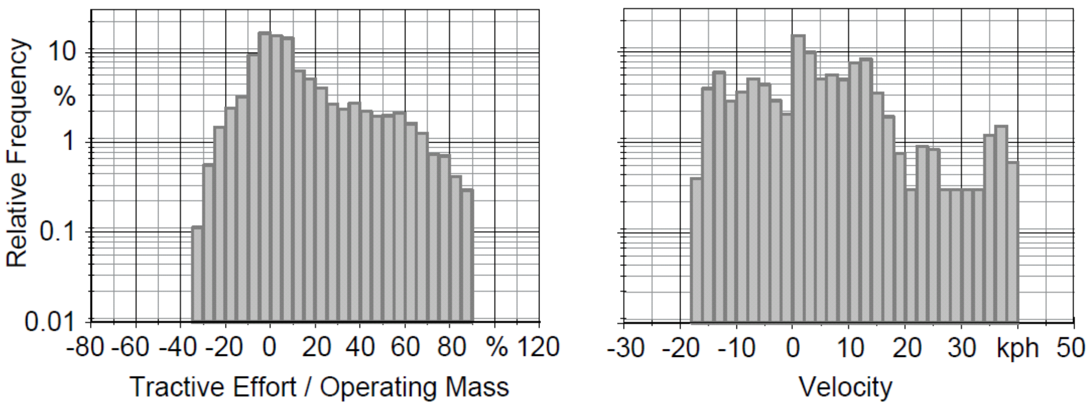


Figure 2: Expected load and speed spectrum for CVT wheel loaders

Functional requirements for future wheel loader transmissions

The following functional requirements are important to provide additional benefit with power split transmissions:

Tractive effort management:

- fast responding torque rise with effective limitation or control while loading the bucket (also to reduce tyre wear and to avoid slippage and soil damage)
- adjustable torque curve characteristics depending on material and surface conditions with max. tractive effort values of 85−95 % of operational mass
- maximum torque capability with diesel engine speeds below 1600 rpm
- robust and dynamic tractive effort control while changing ratios, while inching or when load disturbance occurs

Ratio management:

- high vehicle dynamics with low and optimum engine speeds (the decreased engine speed values need to be more than compensated)
- maximum speeds of 40 kph below 1600 rpm diesel engine speed
- smooth and dynamic acceleration, deceleration and reversing capability for approximately more than 4..6 million reversing operations
- robust fine control positioning and inching function with different load and decoupled engine speed
- standstill capability at slopes without using the brake
- adjustable hydrostatic deceleration or brake function and declutch capability

Power and machine management interface

- PTOs with ratios for reduced engine speeds and different combinations of hydrostatic units for implement, steering, brake, fan or hybrid systems
- electronic machine interface for different power management strategies as well as to provide process data for service and maintenance information

3 HVT – Hydro-mechanical Variable Transmission concept

The HVT concept has been developed and selected after intensive investigations and evaluation of different existing and possible transmission solutions. It is a three range concept with a first hydrostatic drive range and two input-coupled power-split ranges, **Figure 3**.

The first hydrostatic drive range enables efficient digging with precise, dynamic and adjustable tractive effort management control at low engine speeds. The power-split ranges increase efficiency for travel speeds and are optimized according to speed and power distributions in different wheel loader operations.

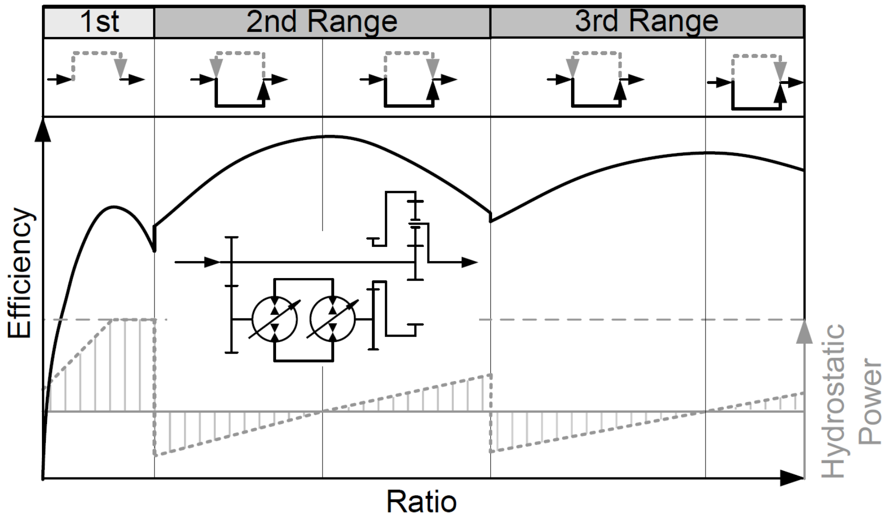


Figure 3: HVT transmission concept

With this setup, the hydrostatic capability of maximum tractive effort with little input power and mechanical decoupled control is combined with high power-split efficiencies at travel speeds.

To reduce wear, reversing and tractive effort management is realized by hydrostatic ratio control and fast range changes (below 200 ms) at synchronized clutch speeds. The three range concept is able to realize the high ratio spread for drive and working strategies at optimized engine speeds and torques. The range setting balances low speeds and circulating power for robust design [6].

4 HVT design

Model based development strategy

Figure 4 shows the applied model based development strategy. Wheel loader application knowledge and latest development methods were combined for an effective development process [7].

Design and Specification

Figure 5 shows the specified mechanical transmission scheme. An A4VG EP swash plate pump with its integrated closed loop displacement control and the high dynamic A6VM EP bent axis motor with its high dynamic pressure displacement change function realize the hydrostatic variator. This approved combination of two independent swivelling hydrostats provides the capability for precise control strategies as well as for optimized pressures and efficiencies of the hydrostatic power flow path.

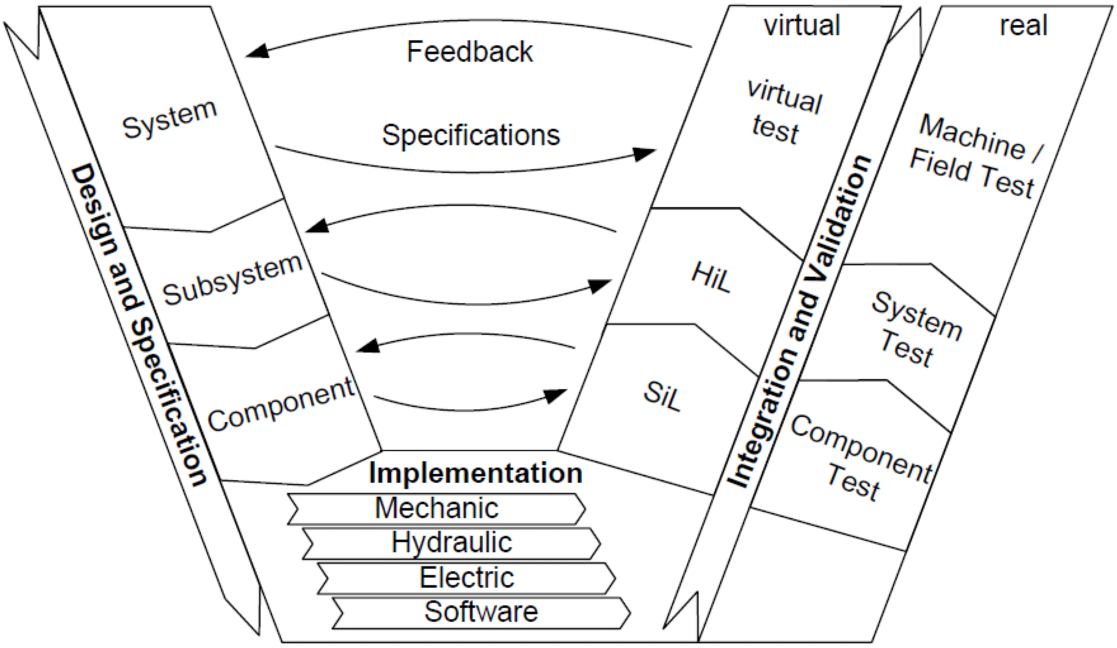
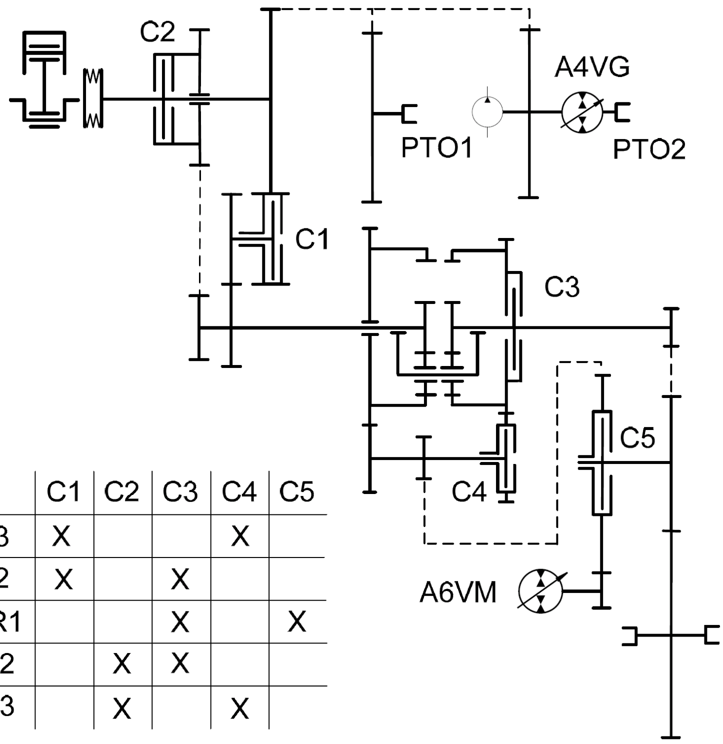


Figure 4: V-model used and applied for HVT development

In the first drive range, clutches C3 and C5 are closed. In the second drive range, the power is split at the input section with the fixed speed coupled A4VG and merged again with two combined planetary gears. Clutches C1 and C2 mirror the input speeds for forward and backward direction in both power split ranges. In the third drive range, C3 is released and C4 is engaged.

PTO1 and the PTO2 allow different setups of implement, steering and hydrostatic fan drive for low engine speed concepts as well as for future implement hydraulic solutions.

The transmissions mechanic, hydraulic, electric and functional specification is developed according to measured and projected load and power spectra and functional requirements for wheel loader applications. The specifications are available as simulations which provide input for the implementation phase.



	C1	C2	C3	C4	C5
F3	X			X	
F2	X		X		
F/R1			X		X
R 2		X	X		
R 3		X		X	

Figure 5: HVT R3 transmission function scheme

Implementation

Figure 6 shows the transmission design of the HVT R3. Its main dimensions and interfaces are compatible to torque converters to allow vehicle integration with little effort for loader manufacturers. The transmission can be coupled directly at the diesel engine flange to realize economic and compact machine setups with combined mounting ports. The input flange provides space for different input dampers. Solutions for cardan shaft inputs (common torque converter machines below 20 t) are possible as well (as presented on Bauma 2010). Mechanical interfaces for different cardan shafts, park brakes and brackets are provided.

The hydrostatic units are derived from serial standard solutions and provide flexibility and robust design. They are connected with high pressure hoses which also damp oscillations. Different hydrostatic units can be combined on the mechanical transmission. **Table 1** provides the flexile arrangement of hydrostatic unit setups within the two HVT power ranges R2 and R3.

The HVT provides two oil flow connections to integrate a cooler. Bypass valve pressure regulation and filters are part of the HVT system.

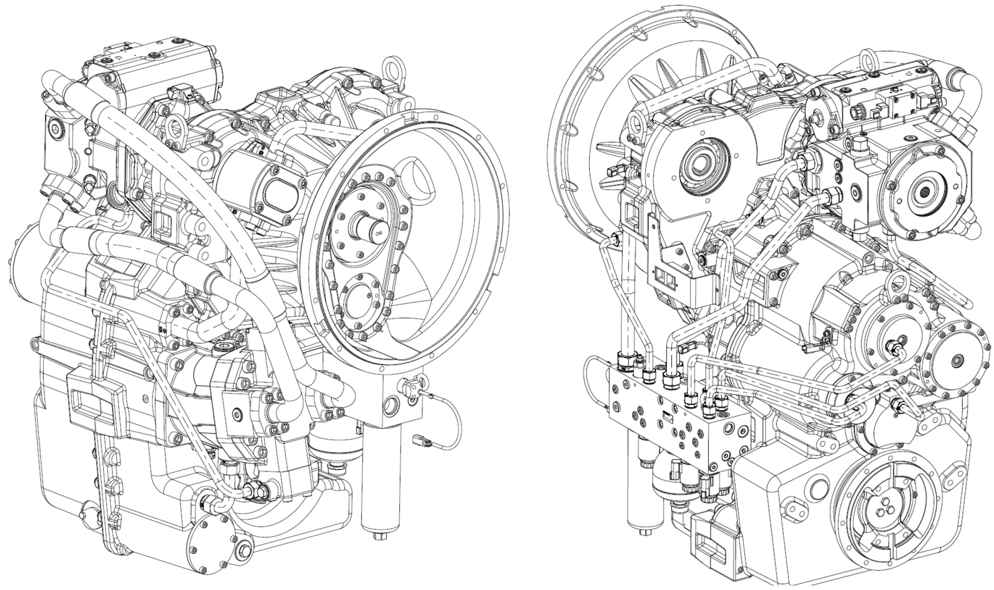


Figure 6: HVT R3 transmission function scheme

HVT	HVT R2	HVT R3
Engine Power	135–195 kW	200–270 kW
Hydrostatic Units	A4VG 85–110 cm^3 A6VM 115–150 cm^3	A4VG 145–175 cm^3 A6VM 170 cm^3

Table 1: HVT transmissions setup

The transmission offers one central connector that collects all actuators and sensors. This allows separated transmission control units as well as integration of HVT software into one central vehicle ECUs (e.g. to share HVT resources with implement hydraulics or wheel loader management software).

The HVT software interacts with machine power management according to CAN J1939 interfaces and provides process information as well as control management strategy signals. Adjustable tractive effort characteristics and ratio strategies for decelerating (including possible declutch and reengaging), comfortable standing at slopes or hydrostatic braking and inching functions are provided.

Integration and validation

The HVT transmission is tested, optimized and approved with

- functional and endurance tests on component test benches (e.g. for valves, clutches, ECU, hydrostats)

- Software and Hardware in the Loop simulations for software and electronic functions
- system hydraulics, performance and functional approvals on development test benches
- stationary and dynamic endurance tests on electric and diesel engine driven test benches
- system approval on roller test benches and field test in wheel loaders

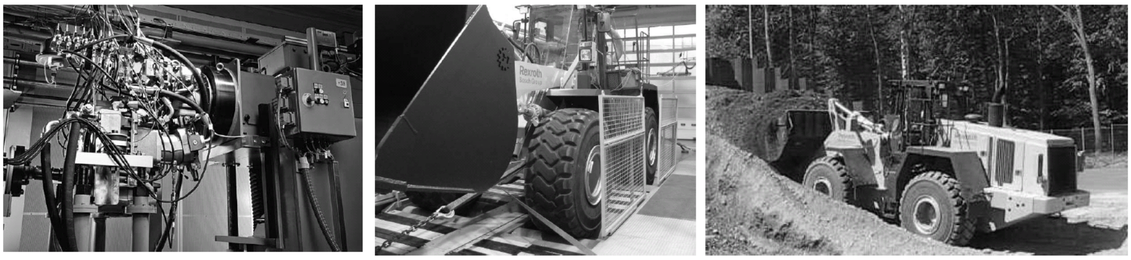


Figure 7: HVT transmission on development test bench, dyno and field test

Transmission efficiency

Figure 8 shows the efficiency gain of the HVT transmission compared to torque converter with the assumption of constant max. engine idle speeds as measured on transmission and roller test benches. During low operational speeds (digging in the pile), the required HVT power for max. tractive effort in standstill is only ~35% compared to the torque converter. This power difference is available for the implement hydraulics to increase productivity or to save energy during loading operations.

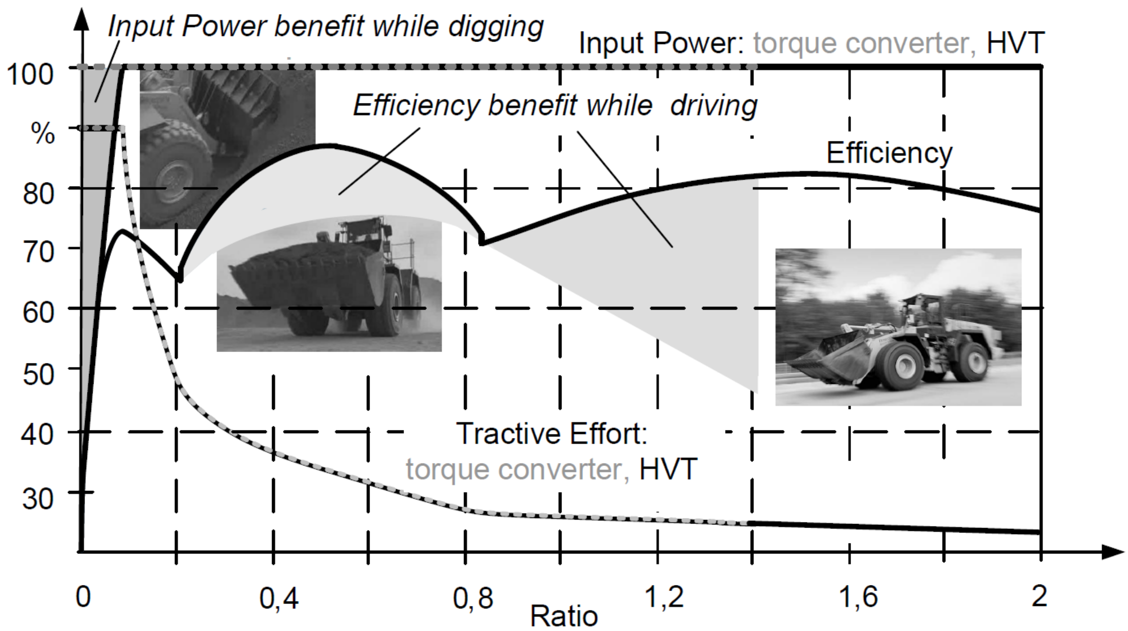


Figure 8: HVT efficiency potential compared to torque converter transmissions

At operational travel speeds, the highly efficient power-split range provides the capability to improve acceleration with lowered engine speeds. The ratio spread exceeds the torque converter capabilities above ratio 1.4 to realize high end speeds and fast travel operations such as 40 kph below 1600 rpm. This high ratio spread enables dynamic wheel loader operations with very steady low engines speed rates.

Ratio and tractive effort management

Figure 9 shows on the left side a measured dynamic reversing procedure which is performed without proportional friction clutches. Ratio setting and range changes are realized by displacement control of the hydrostatic units and very fast changes of engaged clutch combinations at synchronized speeds. The range changes are performed with high torque stability. Efficiency steps and differences between the drive ranges are compensated during transitions with a special algorithm.

The diagram on the right side demonstrates the tractive effort management capabilities to raise torque dynamically but smooth while driving into the pile. For filling the bucket, the torque can be controlled on adjustable levels. Inch pedal functionality can be used for this as well as setting or adjusting different tractive effort curves with operational elements.

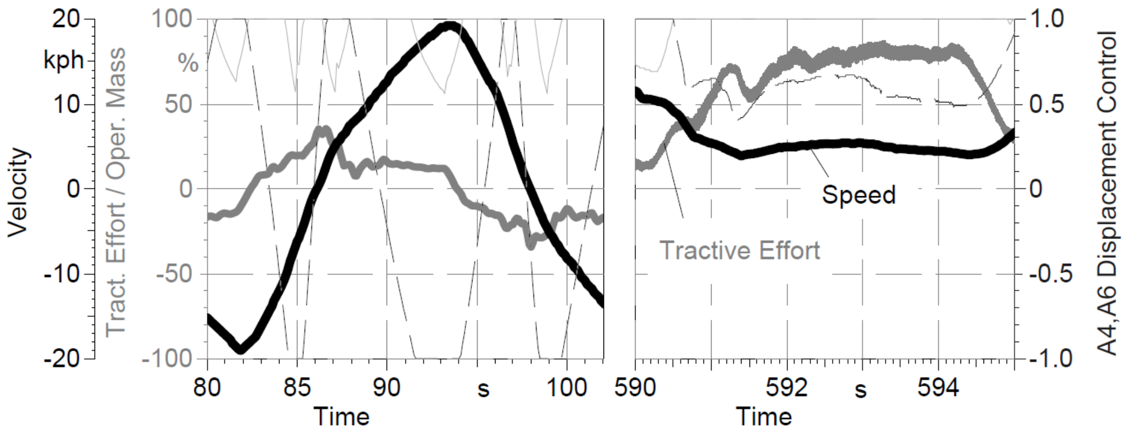


Figure 9: HVT reversing, range change and tractive effort performance

Fuel saving potential in combination with CVT power management

In partial load conditions, the HVT provides the capability to optimize the engine operation point by raising load. **Figure 10** provides one example of this potential compared to a torque converter transmission. Torque converter input power is dependent on input speed level. Contrary to this, CVT technology like the HVT provides speed-independent functionality and make it possible to use the entire map of diesel engines including engine brake torque during deceleration.

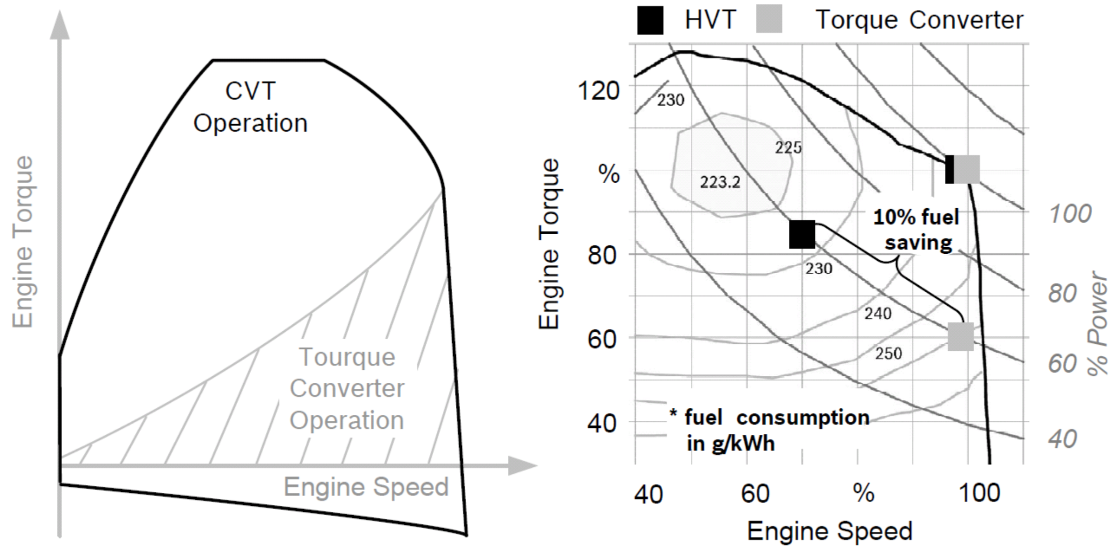


Figure 10: HVT CVT benefits in partial load conditions

Figure 11 provides the fuel saving potential of HVT compared to a 4 speed torque converter transmission for some specific operations of a 24t wheel loader. Transmission efficiency improvement and the engine operation potentials are highlighted separately.

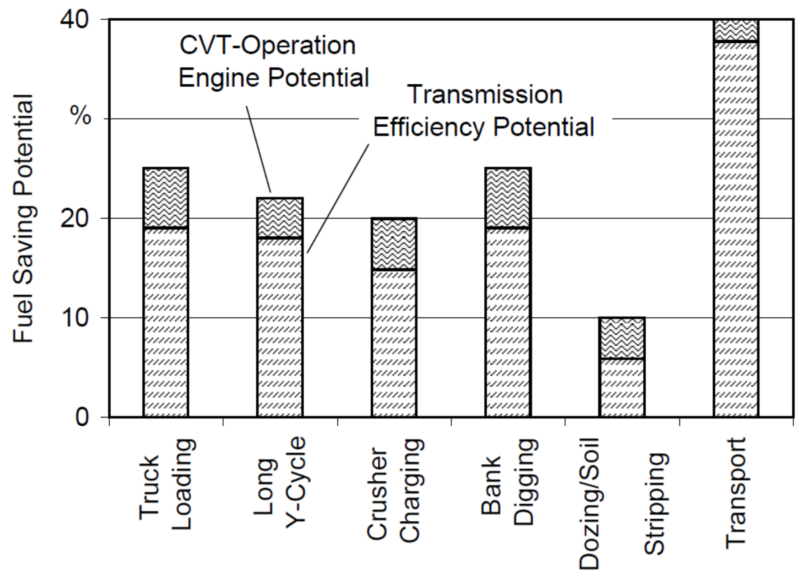


Figure 11: Fuel saving potential of HVT R3 in a 24 t wheel loader

5 Summary

The HVT R3 power-split transmission provides efficiency and automation benefits and fulfils the challenging requirements for future high technology wheel loader transmissions. The HVT was presented by Bosch Rexroth and Dana on Bauma 2010 and on ConExpo 2011 and will be introduced to the market from 2012 on. In order to further develop, manufacture, and market HVT, Bosch Rexroth and Dana established the Dana Rexroth Transmission joint venture located in Arco, Italy.

The HVT fits in with the Rexroth product range for wheel loaders and related applications. The system can be integrated into machine architectures and combined together with implement, steering, brake and hydrostatic fan drive; solutions to support wheel loader manufacturers to face current and future challenges (see **Figure 12**).

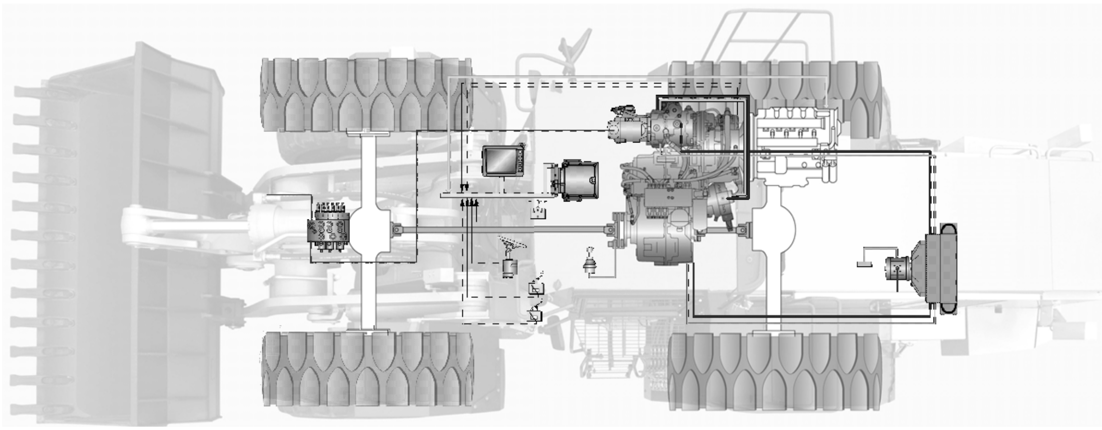


Figure 12: HVT system solutions for wheel loader applications

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