Power split Hydro-mechanical Variable Transmission (HVT) for off-highway application

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Abstract

Nowadays the needs to fulfill severe emission standards and to reduce the mobile machine operative costs have driven the off-highway industrial research towards new solutions able to increase the overall vehicle efficiency. Within this scenario, smart power split transmissions demonstrated to be a very attractive technology able to achieve the fuel consumption reduction targets, increasing the machine working cycle productivity. Compared to the standard technologies (such as Torque Converters - TC), the power split hydromechanical varible transmissin (HVT), designed and developed by Dana Rexroth Transmission Systems S.r.l. (DRTS), is able to fully decouple the engine to wheel behavior during the machine working cycle, with an higher efficiency than a pure hydrostatic transmission. Due to this fundamental characteristic, the HVT allows the engine to work next to the maximum efficiency point, consequently it is possible to downsize the engine to further increase the fuel saving. The analysis of the field test performed by an off-highway vehicle (Kalmar Cargotec DRG Gloria 450 reachstacker) equipped with a DRTS HVT has been shown along this paper; particular attention has been given to the cycle load spectra, the fuel consumption and the working cycle productivity through a comparison with standard TC technologies.

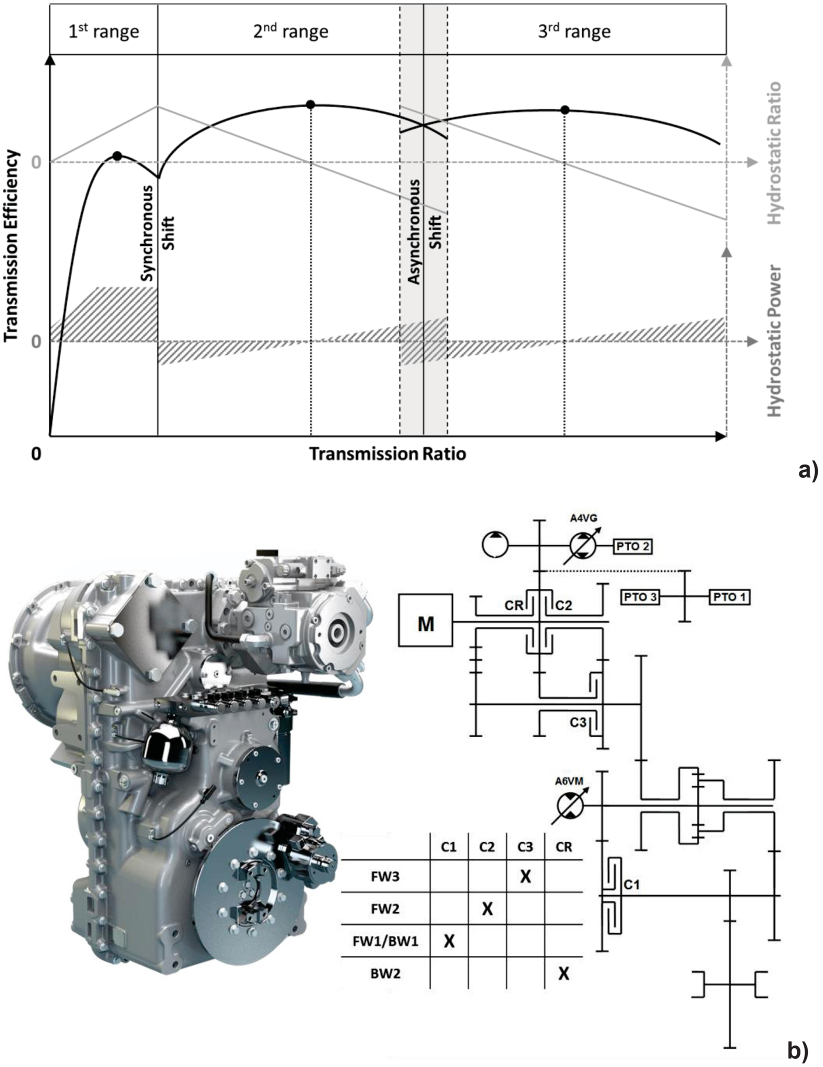
KEYWORDS: Power Split Transmission, Fuel consumption, Field Test, Reachstacker

1. Introduction

Hydro-mechanical power split transmissions (HVT) have had a wide diffusion within the agricultural market since a lot of years due to their higher efficiency compared to a pure hydrostatic drive and due to a higher control flexibility compared to a pure mechanical transmission. The biggest advantage of the HVT is the possibility to fully decouple the engine to wheel behaviour, allowing the engine to work within its maximum efficiency field. Due to the demand increase of more efficient drive lines, able to increase the overall vehicle efficiency, reducing the fuel consumption to fulfil the severe emission requirements and maintaining high dynamic performance standards and productivity, many authors analysed the application of the HVT. They analyse the HVT technology on different fields such as passenger transportation (/1/, /2/, /3/) and off-highway (/4/, /5/, /6/) that usually have higher requirements in terms of drive comfortability and dynamic control than the agricultural market. Sprengel et al. in /1/ and Macor et al. in /3/ underlined the fundamental impact on the fuel economy of the transmission control system for passenger applications. With a similar approach, Murrenhoff et al. in /4/ discussed the importance of a smart control strategy on HVTs within the off-highway markets. The present work analyses the driving performance and the fuel consumption of a reachstacker Kalmar Cargotec DRG Gloria 450 on a reference working cycle. This vehicle was equipped with the hydro-mechanical power split transmission developed and produced by Dana Rexroth Transmission Systems S.r.l. (DRTS) HVT R2, which is designed for 135 kW to 195 kW net input power applications. Therefore, these results are compared to the performance of a same vehicle equipped with a standard technology (Torque converter ZF 5WG261) and the main drawbacks and advantages are pointed out. Moreover an analysis of a 1250 h field test performed by Kalmar Cargotec DRG Gloria 450 K-motion (equipped with the DRTS HVT R2) is addressed to better understand the real working behaviour of a reachstacker equipped with a HVT.

2. DRTS hydro-mechanical variable transmission (HVT)

The DRTS HVT-R2 is characterized by three fundamental features: the continuous transmission ratio, the input-coupled hydrostatic-mechanical power split architecture with a pure hydrostatic 1st DR and the modularity (hardware and software). The whole HVT R2 working range is divided in 5 DRs: 3 DRs forward and 2 DRs backward. The transmission ratio is constantly controlled by two independent hydrostat units (A4VG swash plate pump and A6VM bent axis motor) provided by Bosh Rexroth AG and by the power flow metering through the hydrostatic branch. Considering the reachstacker application, during working conditions at vehicle speed < 3.5 kph (such as stake approaching and container handling), the HVT pure hydrostatic 1st DR combines a very easy and comfortable control with a high fine positioning behaviour of the vehicle. At higher vehicle speed (2nd and 3rd DR), the power split architecture allows the machine to work with a higher efficiency compared to the pure hydrostatic drive.



	C1	C2	C3	CR
FW3			X	
FW2		X		
FW1/BW1	X			
BW2				X

Figure 1: HVT R2 a) efficiency, hydrostat ratio and power thought the hydrostatic branch as a function of the transmission ratio, b) stick diagram and clutch actuation table.

As shown in **figure 1a**, the range shift between the 1st and the 2nd DR (and vice versa) is achieved without tractive effort interruption in a very smooth way by a synchronous shift (no delta speed on the multi-disk wet clutches). The shifting procedure between the 2nd and the 3rd DR (and vice versa) is performed trough an asynchronous shift procedure characterized by a consistent variable delta speed on the multi-disk wet clutches of about 1000 rpm. This particular shift allows the transmission to adapt the shifting ratio point as a function of the driving conditions load. For the off-highway application, and in particular for material handling, the fully hydrostatic 1st DR (FW and BW) allows an extremely controlled and high dynamic but smooth vehicle reversing without the typical power losses which are occurring in torque-converter and full power-split transmissions (see /6/): with the DRTS power split transmission concept no reversing clutch is needed. Moreover, due to the higher efficiency compared to the TC technology and a smarter implements usage strategy, the HVT allows an engine downsizing to further improve the fuel saving, maintaining high driving performance. Another important characteristic of the HVT is the possibility to use the hydrostatic braking instead the service break which are needed for the TC working behaviour. This reduces the maintenance costs and wear on the mechanical parts. A more detailed description of the transmission behaviour in terms of hardware and software interaction can be found in /7/ and /8/.

3. Kalmar Cargotec reach stacker reference cycle

The fuel consumption and performance investigations were carried out analysing the experimental data collected on two ‘equal’ vehicles (Kalmar Cargotec DRG 450 reach stacker) over a standard reference cycle performed by the same driver (see **figure 2**). Each vehicle was completely instrumented and all the main physical variables, such as the transmission input torque and speed (provided by the engine), transmission output torque and speed, the PTO torque and speed, the hydrostat units speed and delta pressure, the instantaneous fuel consumption, the vehicle speed, etc. were collected with a sampling time of 0.01 s. The reference cycle was designed by the Kalmar Cargotec experts to represent a typical reachstacker working cycle. The reference container handling working cycle consists in moving the container from the stack ‘A’ to the stack ‘B’ and back to the stack ‘A’ following the path as depicted in figure 2. The reference vehicle and the K-motion vehicle configurations are summarized in **table 1**.

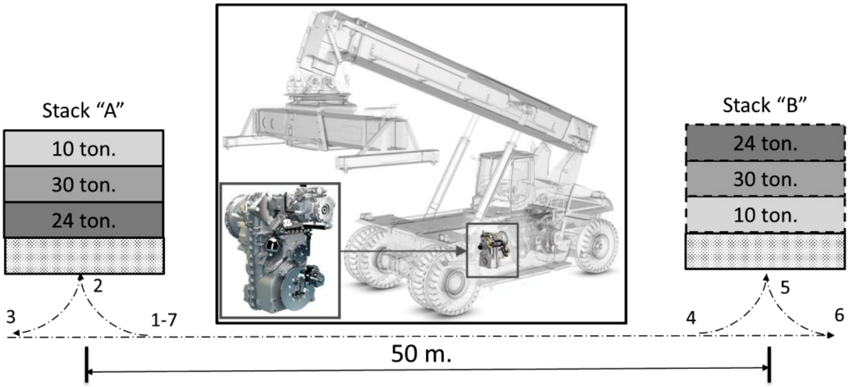


Figure 2: Fuel consumption and performance evaluation reference cycle

	Reference technology	**K-Motion**
Machine	Kalmar Cargotec DRG Gloria 450	Kalmar Cargotec DRG Gloria 450
Empty vehicle mass	66400 kg	66400 kg
Drive axle	Kessler (Differential and hub reduction)	Kessler (Differential and hub reduction)
Transmission	**ZF 5WG261 (TC)**	**DRTS R2 (HVT)**
Engine	**Volvo TAD 1360VE Tier IIIB/4i (256 kW / 1900 rpm)**	**Volvo TAD 872 Tier IV/4f (210 kW / 2200 rpm)**

Table 1

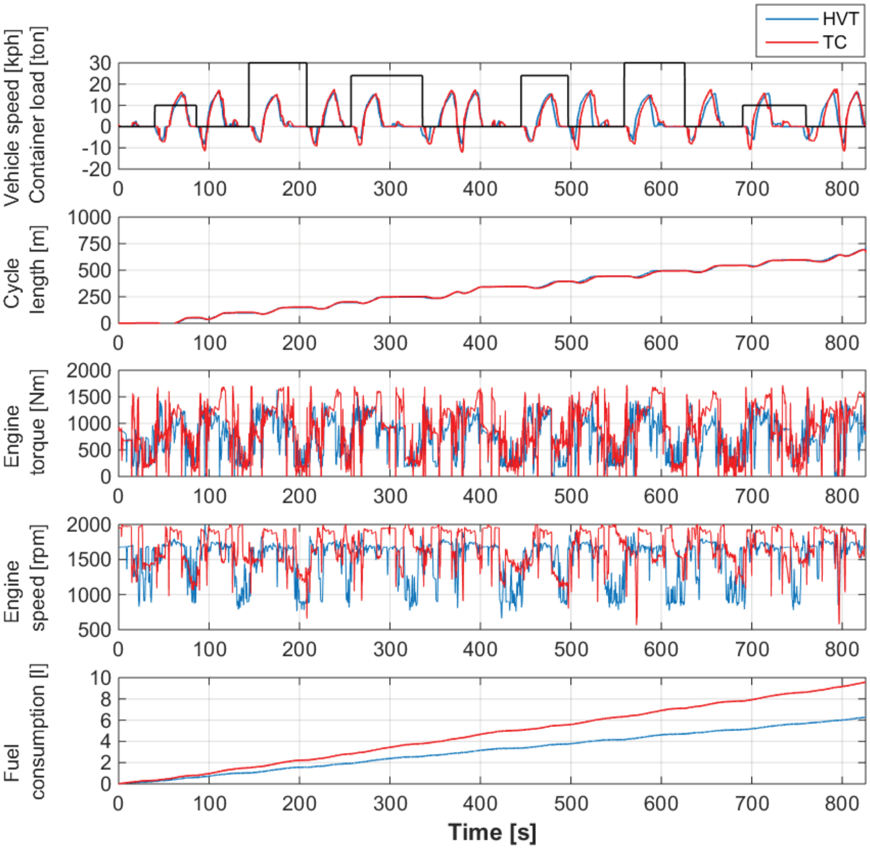


Figure 3: performance and fuel consumption charts. K-motion with HVT (Blue) vs reference technology with TC (Red)

During the cycle performed by the reference vehicle no de-clutch (or lock-up clutch) was used, therefore the TC was always working during the high speed vehicle manoeuvres with high power losses. Due to the higher efficiency of the DRTS HVT compared to the reference TC transmission, the K-motion vehicle was equipped by a smaller and more efficient engine able to fulfil anyhow the entire envelope of vehicle power demand. **Figure 3** shows the main performance such as the vehicle speed, the cycle length and the engine input torque and speed and the absolute fuel consumption for the K-motion vehicle (HVT - Blue) and the reference vehicle (TC - Red) respectively. Considering the overall driving performance, the K-motion vehicle is able to fulfil the driving dynamics required by the cycle and it can guarantee the same productivity of the reference vehicle. Moreover the reachstacker equipped by the DRTS HVT R2 and a new generation engine is able achieve a fuel saving equal to 34.6 % compared to the reference vehicle; the K-motion measured fuel consumption was equal to 6,26 l/cycle (≈27.3 l/h) compared to 9.57 l/cycle (≈41.7 l/h) of the reference vehicle. Further analyses carried out on a vehicle equipped by a TC with the lock-up clutch system, on the same reference cycle, were characterized by a fuel consumption equal to 8.97 l/cycle (≈39.1 l/h). Furthermore, due to the lower average engine speed (≈1500 rpm vs ≈1900 rpm) of the K-motion vehicle compared to the reference one, the working noise was reduced by 6 dB, improving the drive comfortability.

4. Kalmar Cargotec DRG Gloria 450 with K-motion reach stacker field test

The field test was carried out at the Oslo harbour from February to May 2015 for a total of ≈1250 working hours. The vehicle was completely instrumented similarly the one which performed the reference cycle test and all the main variables were collected with a sampling time of 0.01 s. The field test evaluation was carried out to analyse the load spectra ‘time share’ on the transmission output shaft, the FW PULL working transmission efficiency, the PTO power and the transmission input power and speed. All these data are represented over a non-dimensional (n_{out},T_{out}) chart. During the data post-processing, no idling phase (engine speed < 800 rpm, vehicle speed = 0 kph and without implements usage) was considered to better underline the vehicle working conditions. The ‘time share’ charts are shown in **Figure 4** and **5**; the red curve represents the transmission theoretical maximum tractive effort at 1800 rpm engine speed. Just for graphical purposes, the time share chart was divided in 3 charts named figure 4, 5a and 5b that represent the usual, the rare and the very rare (and measurement spikes) working conditions respectively.

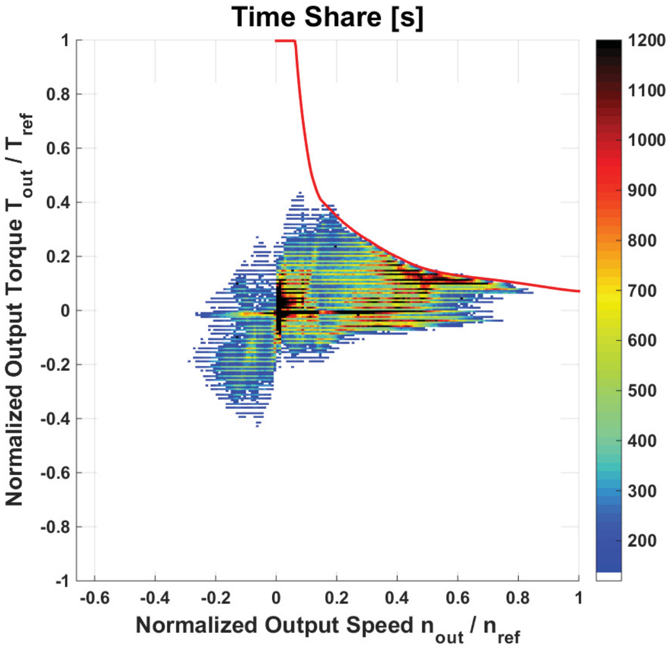


Figure 4: Time share over the (nout,Tout) chart, 'high' time share from 120 s to 1200 s (usual working conditions). The red curve represents the theoretical maximum tractive effort at 1800 rpm engine speed

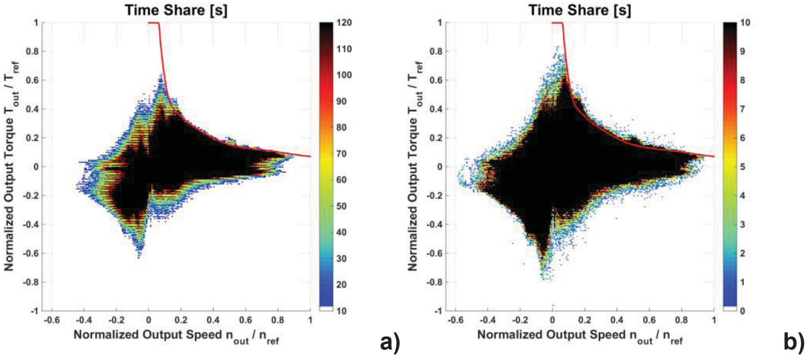


Figure 5: Time share over the (nout,Tout) chart. a) 'low' time share from 10 s to 120 s (rare working conditions), b) negligible time share from 0 s to 10 s (very rare working conditions and measurement spikes). The red curve represents the theoretical maximum tractive effort at 1800 rpm engine speed

In each chart, the black fields represent the out of scale 'time share' values (higher time shares); notice that the black field within the chart in figure 5a represents the load spectra chart shown in figure 4; in the same way, the black field within the chart in figure 5b represents the load spectra chart shown in figure 5a. The time share on the output shaft represents how long a discrete load class (characterized by an average n_{out} and an average T_{out}) occurs along the entire tests. Using the time share indicator it is possible to directly identify the more frequent working regions of the transmission. The time share is usually represented over the 4 quadrants n_{out}-T_{out} chart; the 1st and 3rd quadrants represent the transmission PULL FW and BW working behaviour respectively. The 2nd and the 4th represent the transmission DRAG BW and FW working behaviour respectively. **Figure 6** shows the transmission efficiency for partials loads over the 1st quadrant of the (n_{out},T_{out}) chart.

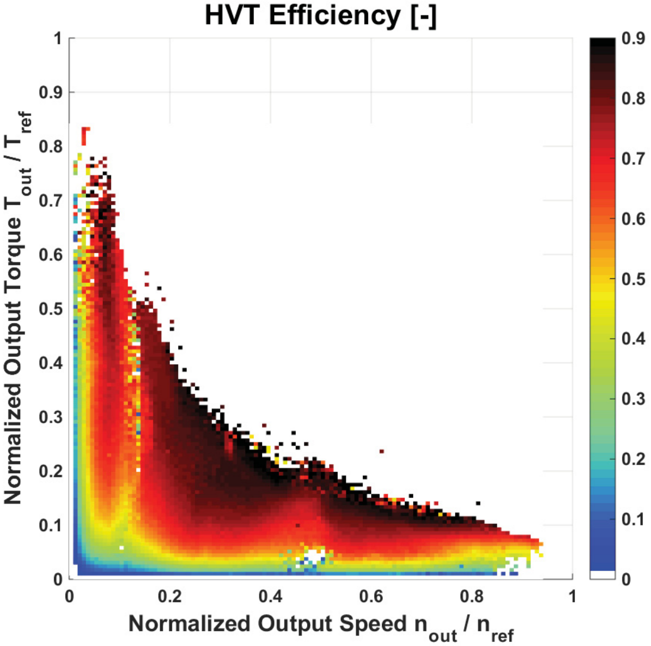


Figure 6: transmission efficiency on the (n_{out},T_{out}) chart (1st quadrant)

During the Oslo harbour field test, the reachstacker working cycle is characterized, as expected, by high time shares across the zero speed point (reverse manoeuvre and fine positioning) and high time shares at vehicle travelling speed ≈13÷16 kph at very high transmission efficiency (above to 80 %). This speed rage usually varies as function of the different track that the vehicle have to complete during the working condition. At partial load (mainly during the reverse manoeuvre and fine positioning) the hydraulic pump and motor are forced to work far from an optimum point, affecting in this way the overall transmission efficiency. Nevertheless, the relatively low transmission efficiency around very low speed and torque (characteristic of the pure hydrostatic drive) is fully compensated by the transmission control preciseness and the driving comfortability. **Figures 7 to 9** depict the transmission input power (both in pull and drag working condition), the transmission input speed and the PTO power respectively.

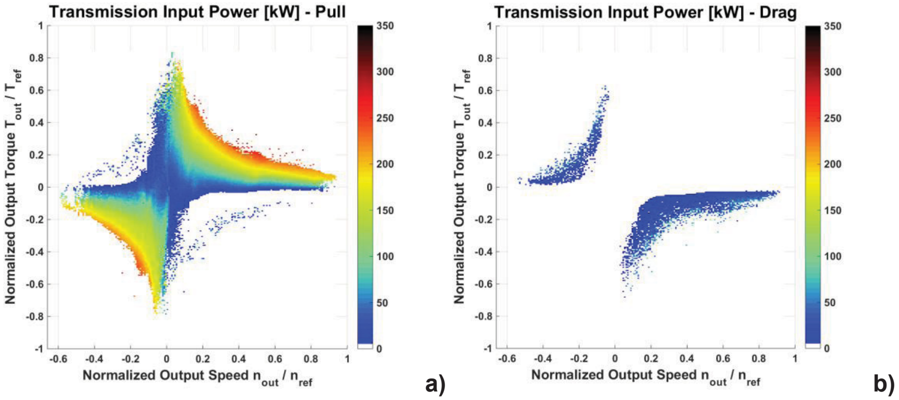


Figure 7: Input power a) Pull condition (positive), b) Drag condition (negative) on the (n_{out},T_{out}) chart

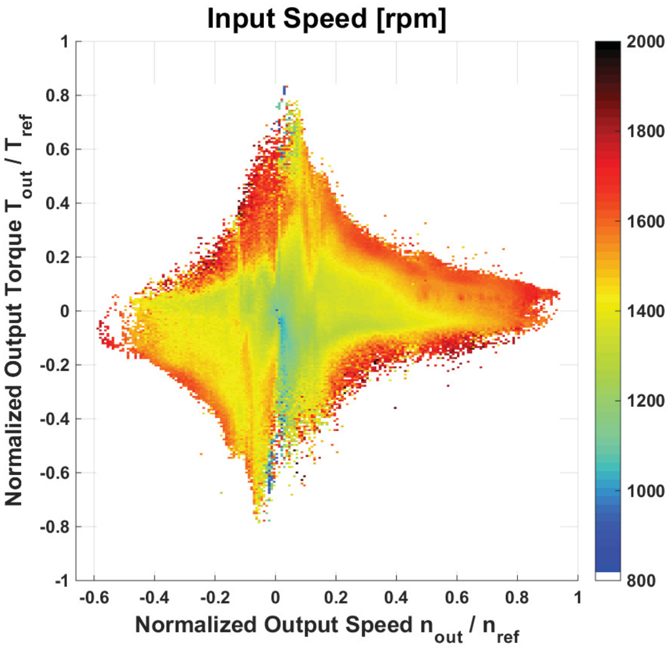


Figure 8: Transmission input speed on the (n_{out},T_{out}) chart.

During the reverse and fine positioning manoeuvres, the engine speed was usually limited at medium-low speed (≈1300÷1400 rpm), to minimize the fuel consumption. The high input speed (over 1600÷1700 rpm) was achieved in pull working conditions to fulfil the high power demand (always at a high efficiency level). High input speed was also achieved during the vehicle drag conditions due to the hydrostatic breaking that minimizes the service brake usage (typical of a TC behaviour), reducing the losses and the mechanical wear on the brake components.

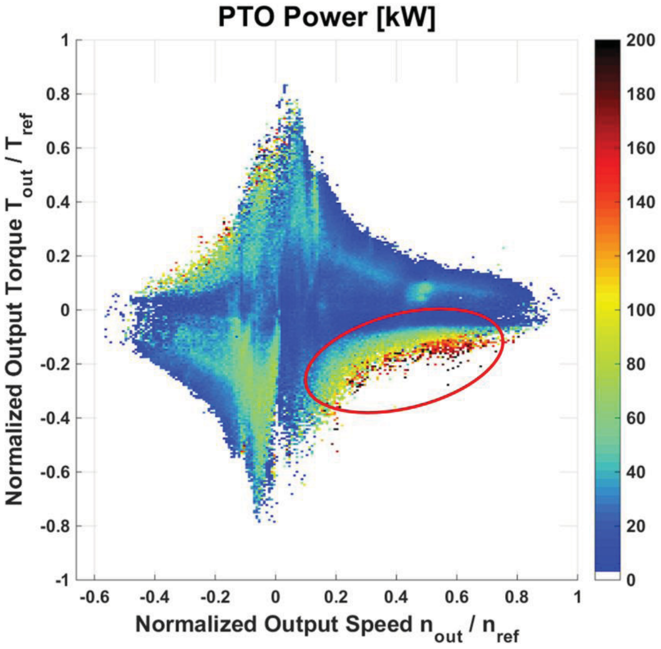


Figure 9: PTO (implements) power usage on the (n_{out},T_{out}) chart

Considering the driving style adopted for the vehicle during the field test, the implements usage was mainly focused during both FW and BW working conditions within low speed/high torque phases; in these working conditions, the HVT technology is able to overcome the TC drawbacks related to the full energy dissipation against the service brake. Moreover, a highest PTO power usage (but with a low time share) was detected in FW drag condition (red circle in Figure 9). During this working phase the power recuperated from back flow related to the vehicle inertia contributes to actuate the implements, reducing in this way the engine power request. In the same condition, instead, the TC technology is not able to recover the power back flow and the engine has to supply the whole power to fulfil the implements requirements as well to compensate the TC losses.

5. Conclusions

A Kalmar Cargotec DRG Gloria 450 reachstacker fuel saving and driving performance were addressed through the analysis of the experimental data collected during a reference cycle test. Moreover the field test data were analysed to better outline a reachstacker typical behaviour under ‘real’ working conditions. Due to the combination of the DRTS HVT R2 (which is able to overcome the TC technology drawbacks during the vehicle implements usage) with a new generation downsized engine, the K-motion system demonstrated to be much more efficient than the reference TC technology. In fact, the K-motion reached a fuel consumption of 6.26 l/cycle (≈27.3 l/h) compared to 9.57 l/cycle (≈41.7 l/h) of the reference vehicle, with an overall fuel saving equal to 34.6 % at the same productivity. Further tests, performed on different cycles, characterized by heavier container handling (up to 40/45 tons) and by a more sophisticated driving strategies, demonstrated that the K-motion is able to reach peak of fuel saving up to ≈40 % compared to the standard TC technology. Considering all the results in terms of fuel saving and performance shown along the present work, the K-Motion system (DRTS HVT R2 combined to a smart implements usage and optimization performed by Kalmar Cargotec) represents the new state of the art within the off-highway material handling drive-train technology.

6. Acknowledgments

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8. Nomenclature

PTO	Power Transmission Output – Hydraulic implements power port	
DR	Drive range	
FW	Forward drive	
BW	Backward drive	
n_{out}	Transmission output speed	rpm
n_{ref}	Transmission maximum reference speed	rpm
T_{out}	Transmission output torque	Nm
T_{ref}	Transmission maximum reference torque	Nm
$ts_{(nout,Tout)}$	Time share at n_{out} and T_{out}	s