

Torque Control for Mobile Machines

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The movement of a vehicle is determined by the torque acting at the wheel. With the speed-controlled engine in mobile machines, the torque characteristics at the wheel are determined by the transmission. Traditionally, this is realized with the inherent mechanic-hydraulic torque behaviour of the components, like a torque converter or an axial piston pump. The disadvantage of this approach is the missing flexibility, resulting in trade-offs like low fuel efficiency or high effort for the realization of control functions. In contrast, the ongoing electrification of mobile machines is the enabler for a new, much more flexible technological approach for hydrostatic drive trains: Torque Control.

Keywords: Hydrostatic Transmission, Vehicle Control, Power Management, Efficiency, Torque Control,

Target audience: Mobile Hydraulics, Mobile Electronics, Mining, Construction, Material Handling

1 Introduction

Due to the rising acceptance of electronics in mobile machines, OEMs strive, besides possible cost reductions, for functional improvements enabled by smart control algorithms. Mostly in the focus are drive modes with various characteristics, consumption reduction and assistance functions. Additional component costs are low; however, the development effort for software is crucial. The main reason why nevertheless many OEMs decide to develop the control software by themselves is the target of offering machines with a flexible and unique behaviour and functionality. In order to control the vehicle, besides software and machine application expertise also deep hydraulics knowledge is applied.

For large machine manufacturers the development effort, together with the applicable development processes for functional safety, is acceptable – smaller OEMs on the contrary need to find the right level of freedom to design the machine without being overloaded by the development effort. Additionally, the companies with a high level of systems and software engineering show a tendency of changing the focus – from component and system control to advanced vehicle functions like automated working as well as connectivity-enabled functions.

In contrast to the existing drive controllers for mobile machines, the idea of Torque Control is to develop a system control for the hydrostatic drive train that is completely decoupled from the vehicle function. The interface to the hydrostat controller is a torque command and a power limitation. In this way, it is the optimum basis for integration in vehicle software architectures without influencing the drive characteristics. Additionally, this interface, based on physical values, is also a suitable solution for power management and autonomous driving functions.

2 State of the art

The focus applications of Torque Control are mobile machines with high demands on acceleration and deceleration behaviour, typically realized by automotive control characteristics. This means that, like in a passenger car, the drive power is a function of the pedal position. These typical applications, e.g. wheel loaders, fork lifts, telehandlers and communal vehicles, are characterized by their huge variety of use cases like loading operations, material handling or dynamic surface works like sweeping or compacting. Automotive driving can be seen in contrast to

proportional driving, where the driver interface, for example a speed lever, is used to command a load independent drive speed.

2.1 Drive train solutions

The typical drive train solutions in the applications named are hydrodynamic torque converter transmissions and hydrostatic transmissions. In the recent years, the importance of hydrostatic transmissions has been continuously growing. The hydrostatic drive is already the standard solution for small machines like compact wheel loaders. In combination with 2-speed, summation or power-split gearboxes, the application range is continuously growing, replacing torque converters even in machines with a service weight of up to 65 tons /1/. The reason for the success of the hydrostatic drive is the decoupling of engine speed from tractive effort, leading in typical work cycles to fuel savings of up to 20%, due to the higher efficiency and increased ratio spread with power-split solutions even up to 35% compared to hydrodynamic concepts /1, 2/. However, in some applications and especially in the American and the Asian market, the torque converter transmission is still the preferred solution due to the specific, comfortable driving characteristics.

Besides the niche quantity of big mining machines, the only application with significant numbers of electric drives is today the forklift, due to the high time share of indoor operation. The same motivation currently leads to similar developments in the field of small construction and agricultural machines. Another reason for the expected technology transition to electric drives are zero-emission requirements in urban regions, mostly relevant for small to medium size machines below 20 tons. For machines above 20 tons, the main driver for electrification is the efficiency, even if the gain versus the power-split transmission is in the lower one-digit range.

2.2 Hydrostat control

Independent of the used technology of hydrostatic pumps with feedback-controlled displacement or pilot pressure feedforward control, the behaviour of the electronically controlled drive train with automotive behaviour is mostly determined by the applied system control concept. Two approaches with many variants are most typical. The first approach is similar to the classic hydraulically controlled system: The variable motor displacement is set by a pressure feedback controller, with the pressure set point being a function of engine speed. With the assumption of a relative pump displacement of 100% and defined engine speed, controlling the pressure results in controlling the power flow to the pump. This concept is applied either as power limitation or as power control. Consequently, the driver is commanding the drive train power with the drive pedal. The behaviour is very smooth, because the flexibly adopting motor displacement compensates both dynamic load as well as pump flow changes.

The second approach is based on speed control of the motor. In contrast to power control, speed control does not require pressure sensors. This concept is typically characterised by a more stiff drive behaviour, because the driver is controlling the vehicle speed instead of the power. Both concepts work equal at low vehicle speed, while the motor is constantly on full displacement: The pump command is used to control the tractive effort as a function of either engine speed or drive pedal.

The existing control concepts have in common that there is no possibility to directly parameterize the machine behaviour. All software calibration is done on component level, setting currents and pressures based on input signals. Additionally, neither power nor torque information is directly available in all drive situations. Communication with power managers or hybrid modules is challenging or even impossible.

3 Torque Control

The idea behind torque control is that every machine movement is a result of the wheel torque. Understanding the operation of the machine, the wheel torque can be commanded to exactly fulfil the driver's requirements. In a passenger car, the wheel torque is typically a result of the engine torque, multiplied with a fixed transmission ratio in each gear. For a mobile machine this is different. Since the engine is speed-controlled, the wheel torque is a result of the operation point of the stepless transmission, for example defined by the speeds acting on the torque

converter or by the pressure difference in the hydrostatic circuit. The characteristics are primarily determined by the design parameters of the components. With electronic control of the wheel torque, it is possible to define the drive characteristics in the software, even to emulate the drive behaviour of different kinds of transmissions.

3.1 Separation of Component Control and Vehicle Control

In comparison to today's typical hydrostatic drives with automotive characteristics, with torque control the drive strategy and characteristics are separated from the system/component control, Figure 1. The hydrostatic transmission acts as a pure torque source.

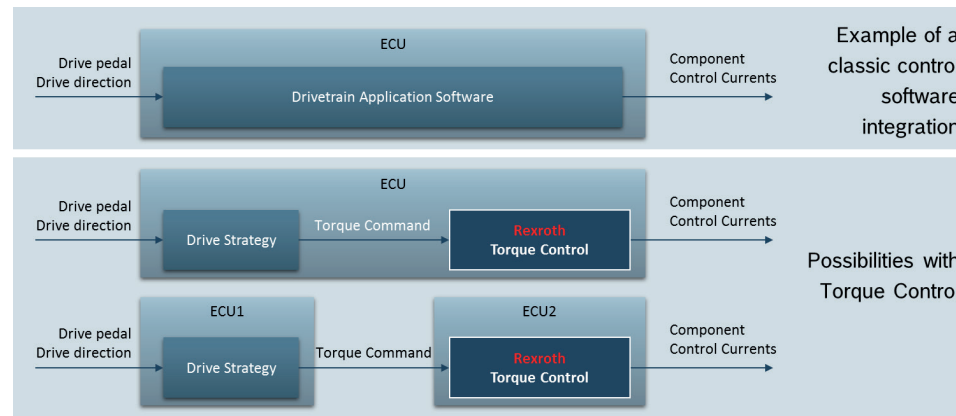


Figure 1: Introduction of Torque Control allows to separate drive strategy from system and component control by a simple, physical interface.

This offers many new advantages:

- Vehicle control is possible without deep insight into the technology of hydrostatics. The vehicle control engineer can design the machine behaviour based on torque and speed values.
- Parameterization of drive behaviour is done on vehicle level (torque, speed) instead of component level (current, control pressure). During commissioning, it becomes much easier to realize an expected drive behaviour.
- The same vehicle control strategy can be used for electric and hydrostatic systems. With the trend to electrification, vehicle software is reusable which reduces the development and maintenance effort.
- Transfer of control software from one machine to another is facilitated. The hydrostat control does not depend on vehicle size or engine power. If machine parameters change, this is handled in the vehicle control.
- The component supplier abstracts the component behaviour, introduces and validates robust control algorithms and provides the standard interface from the machine to the system control level.

The commanded wheel torque may be a function of the engine speed, as it is the case with today's typical drive train solution. Alternatively, it is possible to define the torque as a function of the drive pedal only, so the engine speed is independently controlled. Figure 2 shows the system scope of the Torque Control module with the possible scenario of a CAN interface between the vehicle control unit (VCU) and the transmission control unit (TCU).

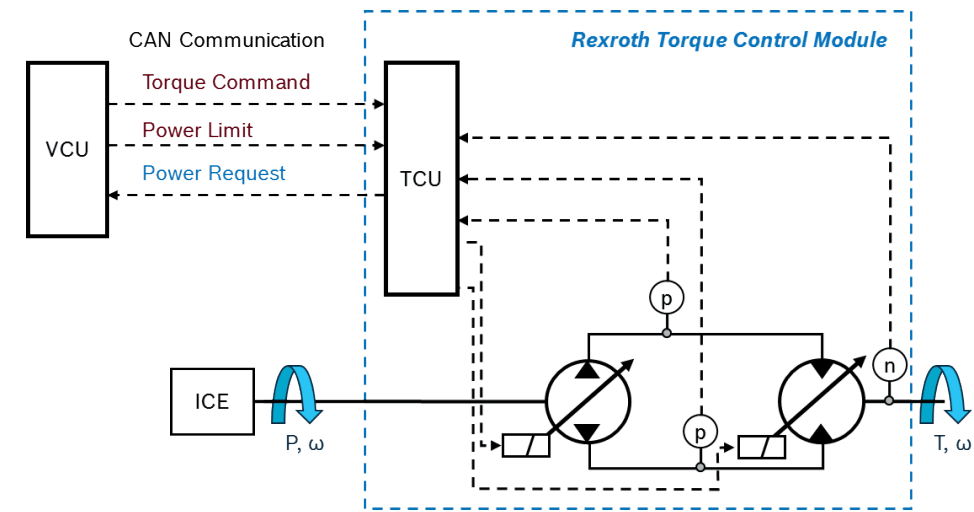


Figure 2: System Scope of the Torque Control module with interface

3.2 Torque Control Concept

The torque of a hydrostatic machine, in this case the hydrostatic motor, is defined as

$$T = \frac{V_{G,max} \cdot \alpha_{rel} \cdot \Delta p \cdot \eta_m}{2\pi} \quad (1)$$

with the displacement volume $V_{G,max}$, the normalized actual displacement α_{rel} , the pressure difference Δp and the mechanic efficiency η_m . That means that a torque request can be fulfilled by fixing the pressure difference and commanding the normalized displacement α_{rel} . This concept is known as secondary control. The disadvantage of this approach is that it needs a variable displacement motor, as well as a solution to switch the torque direction. That is why Torque Control in every time step assumes the motor displacement to be constant, setting the torque only via the variable pressure difference. The pressure is controlled in all four quadrants, which means that the machine is always controllable via the torque command. No matter if the focus is on acceleration, deceleration or drive direction changes, a change of the torque command directly influences the machine behaviour in the expected way. Since the pressure control is done with the pump, any kind of fixed or variable displacement motors can be used. While classic control concepts often have different component control algorithms depending on acceleration, deceleration and direction change, with torque control this differentiation is done on vehicle level. The torque control algorithm itself is realized without any state machines or algorithm switching. In this way it is guaranteed that the resulting wheel torque is continuous and reliable. Although electronics on mobile machine are today a proven technology, torque control is developed to work even with a pressure sensor malfunction: While the operator finishes his duty, only control precision is reduced.

Figure 3 shows a sample measurement with torque control. In the top graph vehicle speed and engine speed are displayed. The bottom graph shows a comparison of desired difference pressure dp_{des} and the measured pressure difference dp . The pressure controller follows the command with a maximum error of typically 10 bar or approximately 2% of the control range.

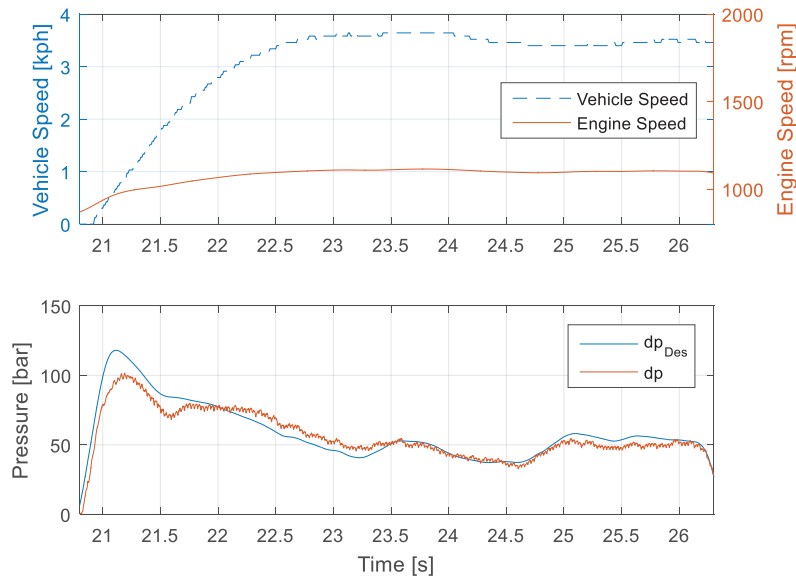


Figure 3: Pressure control with A4VG variable displacement pump

4 Components of the Torque-Controlled Drivetrain

Torque Control is realized with a new generation of Rexroth components specifically designed for the needs of electronic control.

The pump, A4VG series 35, is reduced to the pure functionality of a hydrostatic pump, resulting in a lighter and shorter design. At the same time the pump is optimized for high pressure up to 530 bar, as well as for electronic control: Besides the interfaces for speed, pressure and angle sensors, it is equipped with the new and very precise control valves MHDRE05, specifically optimized for pump control. With the direct integration of the valves, the pump allows highest swivel dynamics. However, depending on the application, also other pumps like A4VG series 32 or series 40 are suitable for Torque Control.

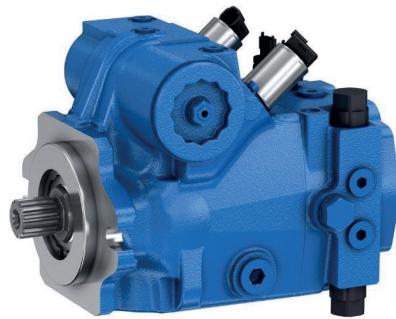


Figure 4: Axial Piston Pump A4VG Series 35, optimized for electronic control



Figure 5: Rexroth pressure sensor PR4 with digital SENT interface

The new pressure sensors PR4 are derived from Bosch automotive sensors with proven reliability, adopted to the needs of mobile machines. Since the robustness of the measurement signal highly depends on the signal transfer and signal transformers, with this sensor the analogue signal chain is replaced by the digital SENT technology. Besides the increased signal robustness, the sensor offers digital diagnosis as well as a temperature signal.

The hydrostatic system is completed with any kind of constant or electronically displacement-controlled variable hydrostatic motor, or multiple motors. The combination with all kinds of transmission solutions is supported: Summation gearboxes, multiple speed synchronizer or power shift gearboxes, even power-split transmissions are possible to be integrated with Torque Control.

5 Power Management

Power is required for performing any task in the mobile machine. The engine capability limits the available power, depending also on the actual engine speed and available air mass. Additionally, power must be shared especially between the main consumers drive train and implement hydraulics. In the classic loading machine, the drive pedal controls the engine speed and thus the available power. The inch pedal prioritizes, among other functions, the power flow to the implement hydraulics. This is the main reason why it is not easy to operate a working machine: Besides driving and moving the implements simultaneously, the operator is also responsible for managing the power flows. The fuel efficiency of the machine depends highly on his skills. Many manufacturers offer trainings for fuel-efficient operation of the machine in order to achieve the lowest consumption possible.

The idea behind Rexroth Power Management is to facilitate the machine operation by transferring this responsibility from the driver to the control logics. Implements are controlled with the joystick only; propulsion is commanded with the drive pedal. The operator does not need the inch pedal anymore. However, it may still be available to preserve the classic HMI.

5.1 Concept of Power Management

The basic idea of central power management stems from the requirement that the power consumed by the system should be exactly the same as the power made available to the system /4/ and to limit the power flow to some low priority consumers to protect the energy supply of higher priority power devices in the case of lack of power.

The Power Management presented here coordinates the energy flows to and from the central power distribution node (usually the diesel engine crankshaft). Every power system connected to the central power node (e.g. drive train, hydraulic working functions) computes the required power for its operation. The power manager collects all these demands, compares them with the available power of the power sources (e.g. diesel engine, storages) and assigns available power to each requester, which must not be exceeded, Figure 6. In the case of lack of power, the power management limits the consumption of the subsystems. The power sharing is flexible – in this way, it is e.g. possible to reduce the power flow to both drive train and implements proportionally, so the overall machine movement gets slower, but stays synchronized.

Generally, there are always consumers or losses on the machine that cannot be considered with a precise power estimation. That is why the Power Management generally includes a classic load limiting control in order to achieve a 100% engine power usage without overloading the engine.

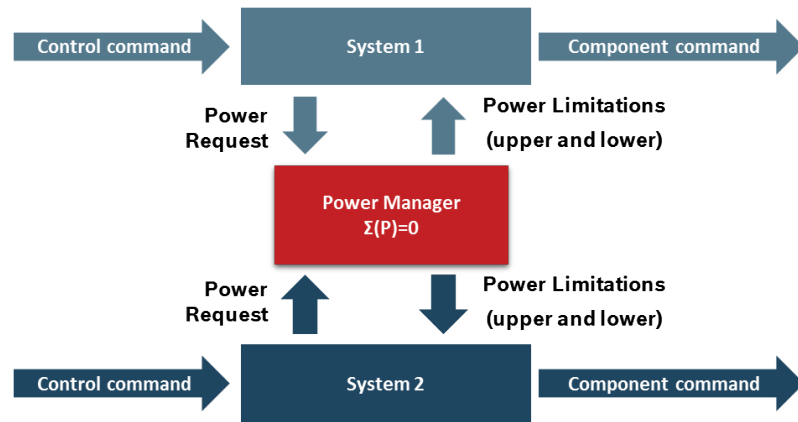


Figure 6: Concept of Power Management with two sample systems

5.2 System Architecture

With Torque Control, the complete control architecture has been reconsidered with a focus on decentralization and modularity.

The result is a matrix structure, as it is shown in Figure 7. The control functions are separated into machine subsystems in one dimension, while in the second dimension each subsystem is organized in layers referring to the controlled system scope. There is no direct communication between the subsystems. All power-related communication is handled via the Power Manager. Each power system communicates with the power management without knowing about the existence of other power systems. Thus, there is no great effort if some further power systems need to be added into the system. Subsystems can be easily integrated additionally or replace existing subsystems. For example, the Engine Control System could be replaced by an electric power source system. Additionally, hybridization as a key option of future mobile machines is regarded and handled in the system concept: A mobile machine can have one or more main power consumers, but also sources.

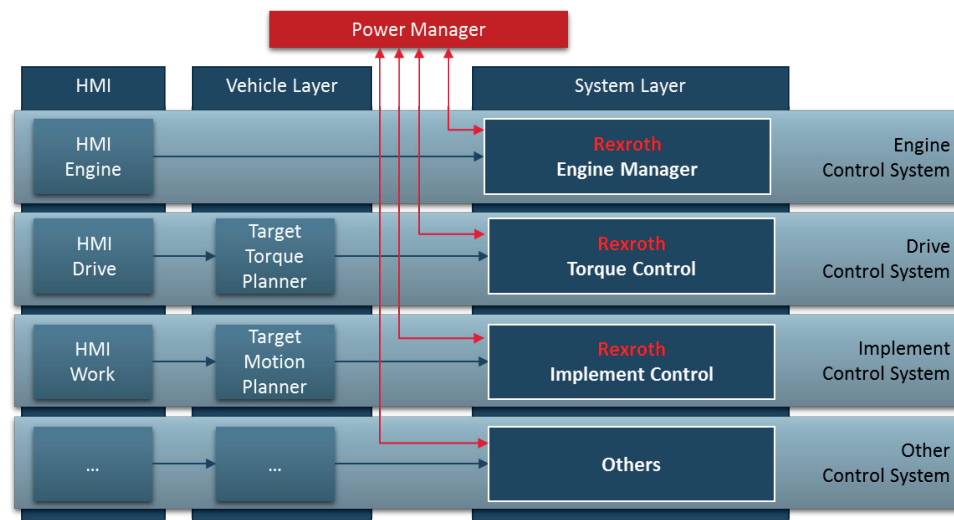


Figure 7: Control system architecture with power management interfaces

Simple rules ensure the compatibility with all kinds of control subsystems and technologies:

- **External Interfaces are only available on the responsible architecture layer.** A drive pedal signal is available to the drive strategy (in this case the target torque planner), but not to the transmission control. A pressure sensor signal is available to the transmission control, but not to the drive strategy.
- **Only local parameters are allowed.** The nominal engine power is known by the Engine Manager, but not by the Transmission Control. In this way, all modules can be developed and configured independently.
- **All internal interface signals are based on the physical states speed, torque and power.** This ensures the cross-domain compatibility between e.g. hydraulic and electric systems, as it is needed in hybrid vehicles.

6 Power request based engine control

Since with Torque Control the drive behaviour is decoupled from engine speed, any kind of engine speed commanding is possible. For instance, constant speed is supported as well as pedal-dependent speed operation. However, the probably preferred option is the combination with Power Management, setting the engine to the optimum operation point: The most efficient way to operate a diesel engine is to reduce the speed to the minimum at which the requested power is still available /5/. As Figure 8 visualizes, with a certain power request the lowest possible engine speed results not only in low consumption, but also in zero torque reserve. This means that the responsiveness to load increases is very slow. Taking the torque reserve into account, a higher engine speed operation point is chosen. Accordingly, it is possible to define an operation strategy for minimum consumption as well as for maximum responsiveness, or a suitable compromise of both requirements.

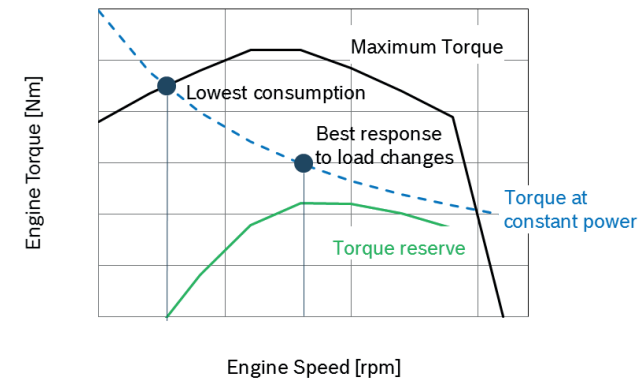


Figure 8: Engine torque map with possible optimization targets of the power manager – lowest consumption or highest torque reserve to achieve fast dynamic responsiveness

Additionally, each subsystem of the machine may have certain speed requirements. Due to the decentralized structure, the Engine Manager does not know about any boundary conditions of the components that need to be respected. For example, the implement system may require a certain lift speed, and a resulting minimum engine speed to realize the related implement pump flow. On the other hand, also the maximum engine speed may be limited, in order to prevent cavitation on the pump suction side. So a second function performed by the power manager is to collect all speed requests and send a minimum and maximum speed boundary of the crankshaft to the Engine Manager.

7 Prototype vehicle

Torque control has been implemented on a 10-ton wheel loader with a 95 kW engine. Maximum power is available in the engine speed range from 1800 to 2200 rpm. The drive train consists of a variable displacement pump A4VG with direct control (ET) and a variable displacement motor A6VM with proportional control (EP), in combination with a two-speed Shift on Fly transmission. The drive pedal directly commands wheel torque, while the engine speed is a function of power and flow demands of the integrated hydraulic systems. Since the engine speed and the drive behaviour are completely decoupled, the engine speed can be varied for implement movements without influencing the drive behaviour. Based on a torque-based parameterization, distinct drive modes are in development to cover the needs of various applications as well as specific markets. With the integrated BODAS DI4 display, the torque characteristics can be continuously adapted to the driver's needs.

Figure 9 shows a measurement of the prototype with acceleration and deceleration phases. The parameterized torque behaviour is derived from the characteristics of a classical hydrostatic drive. The measured torque follows the command, both for acceleration and deceleration. The torque direction is changed instantaneously to follow the driver command without recognizable delay. The engine speed is decoupled from the drive speed and commanded by the power manager. With the current parameterization, the power strategy is to provide maximum dynamics and all available engine power in the working range up to 12 kph, with the target of high productivity. Above 12 kph, the power and the engine speed is reduced, with a focus on fuel saving during travelling.

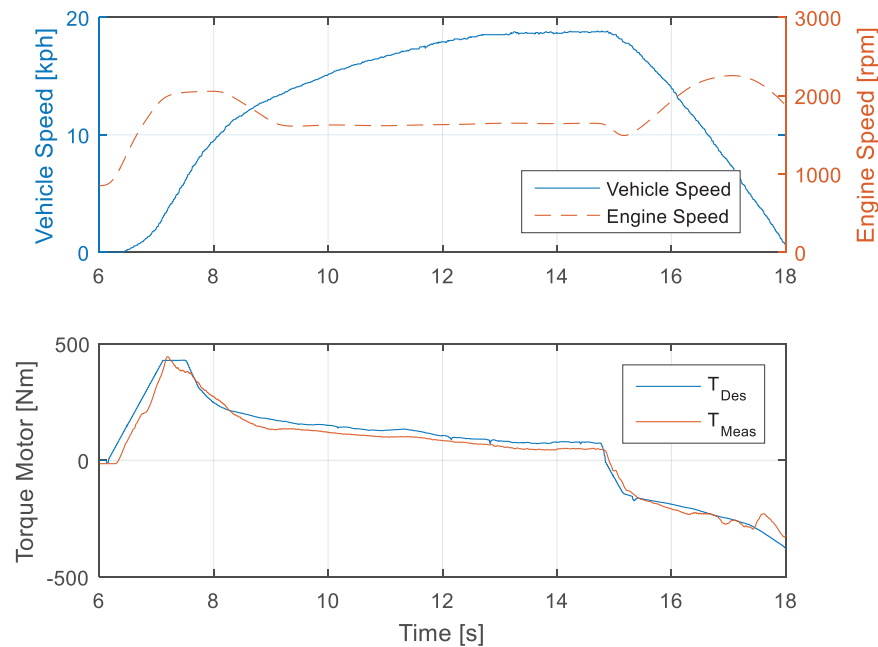


Figure 9: Acceleration - deceleration measurement with Torque Control

8 Summary and Conclusion

Torque Control is a next generation control approach offering highly increased flexibility with respect to the design of drive behaviour, e/e architecture and control function architectures. Since the same vehicle control algorithms can be used for hydrostatic drives, electric drives or any kind of hybrid solutions, development and validation effort are reduced. As the control of the hydrostatic transmission is decoupled from the drive strategy and the drive characteristics of the machine, it is very simple to adopt the machine behaviour to the operator's needs – based on torque and speed values, without any cross-influencing of other functions.

Physical signal interfaces allow the direct communication with power managers and hybrid modules, with the goal of flexible adaptation towards the machine operation strategy, to achieve either high performance or lowest fuel consumption.

Rexroth Torque Control for hydrostatic drives perfectly harmonizes with Rexroth Drive Strategy and Power Management modules. Together with Electrohydraulic Implement Control, a powerful yet fuel-efficient machine concept can be provided.

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