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Measuring and Characterization of a Pedal Electric Cycle (Pedelec) Drivetrain on a Test-Bench for Modelling and Optimization

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***Abstract*—This paper shows the extended characterization of a pedelec drivetrain and the construction of the necessary test-bench. The test-bench construction for a drivetrain only enables thereby reproducible, comparable and precise measurement. This allows the control and electromagnetic design of a pedelec drive to be optimized during development. In addition, parameterized simulation models based on special measurement methods enable simulation-based development of pedelecs. Likewise, the test-bench is able to perform a range measurement of R200 [1] easily and automatically as well as the reachable height. This paper shows the structure, the design and the operation of the drivetrain test-bench as well as the measurement routines, methods and the results of a device under test pedelec drive unit.**

***Index Terms*—Pedelec, Characterization, Drivetrain, Virtual Prototyping, Modelling**

I. Introduction

Focused on urban mobility concepts, comfortable and simple mobility, health and rehabilitation in sport or entering new dimensions in cycling, more and more electric supported bikes (eBikes) exist. A subcategory of these are the pedelecs (pedal electric cycles). These bikes offer electric supported cycling in a low power range, normally without additional license or registration. Characterizations like long-range [1] or reachable height testing, assistance level mode determination, efficiency, regeneration mode, cutoff-time and dynamic control behavior for natural feeling of the pedelec are thereby of interest. But also simulation driven system development and fast prototyping of these drivetrains are more and more focused [2, 3]. Similar to the hybrid electric vehicle development, full system test-benches for pedelecs were developed in the past [4–6].

However, for fast development and research, single drivetrain test-benches offer advantages. Especially for the characterization of the pedelec drivetrain. Additional disturbance due to the tires, the bearings, the cyclist etc. in a full system test-bench shows the necessity of this single drivetrain test-bench. Here the focus is only on the drive unit, the chain and the derailleur. Not only for testing but also in the development of the drivetrains and their control algorithms, a test-bench like this is useful and mandatory. Drivetrain test-benches, which are modular and variable enough for drivetrains of various manufactures as well as covering the whole operation area, cannot be found in literature and are only sparsely available on the market [6] or even proprietary test-benches [7].

The shown modular and flexible drivetrain test-bench enables reproducible and robust measurements, especially in comparison to full system test-benches. This paper shows the development, the design and the operation of a modular pedelec drivetrain test-bench as well as the measurement methods and results of a device under test pedelec drivetrain.

The structure of the paper is as follows: At first, an explanation of the principle of a pedelec and the power flow diagram. Then, the requirements for the test-bench based on state-of-the-art pedelecs are derived. Following the build-up and design of the test-bench is explained. The device under test (DUT) is described and different measurement methods are introduced. Measurement results are shown and explained after this. Finally, a summary of the paper is given.

II. Pedelec - Overview

Pedelecs are allowed to electrically support the cyclist up to a speed of $25\,\mathrm{km\,h^{-1}}$. In addition, the nominal power of the drive unit is legally limited to $250\,\mathrm{W}$. Over short periods of time, higher power output is allowed. In contrast, S-Pedelecs are allowed to support up to $45\,\mathrm{km\,h^{-1}}$ by a nominal power of up to $4\,\mathrm{kW}$. In both cases, the cyclist must pedal to get assistance, this leads to a power flow as depicted in Fig. 1.

In green the power of the cyclist is shown, split in two parts representing the input power of the left and right crank, respectively. Therefore $P_{\mathrm{mec,ri}}$ and $P_{\mathrm{mec,le}}$ are combined to $P_{\mathrm{mec,in}}$. The drive unit uses the power stored in a battery to support the cyclist. The total power in the drivetrain is shown in dark blue. The power shown in light blue is the output power of the pedelec, it is the sum of the cyclist and the power of the drive unit and is the resulting power for the drivetrain of the pedelec. $P_{\mathrm{loss,ped}}$ are the sum of the losses of the pedelec e.g. the losses in the chain and the derailleur. The test-bench presented in [4] is based on this power flow diagram.

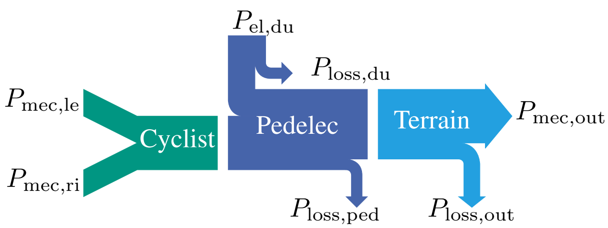

Fig. 1: Pedelec power flow diagram

Drive units can measure the cyclist's torque using various methods. In cases where only the sum of the torque from both cranks is measured [8], the drive unit cannot differentiate which crank the power is applied to. In this case or if only the torque from the left crank is measured, it is sufficient to apply torque to the left crank. The power flow can therefore be simplified like shown in Fig. 2.

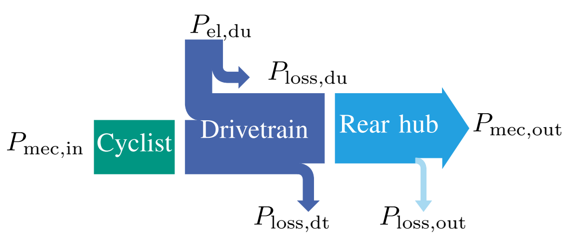

Fig. 2: Simplified drivetrain power flow diagram

III. Requirements

Compared to system test-benches as in [4–6], the drivetrain test-bench presented here is intended to reduce the complexity and uncertainties on one side and of the device under test on the other. The contact between tire and roll is critical because losses occur, the friction coefficient between tire and roll limits the maximum torque and cannot be compared with the real one between tire and road. These factors lead to uncertainties and can be avoided. To do so, the tire should be excluded and instead nearly frictionless form closure contact should transmit the power to the output. This increases the reproducibility and accuracy of the measurement, as well as reducing the inertia to increase dynamic.

The test-bench has to be able to apply the maximum torque and cadence of cyclists as input and pick up this power with the added drivetrain power at the output. For the input, a cyclist pushing with a weight of $100\,\mathrm{kg}$ into the pedals is assumed. With a crank length of $175\,\mathrm{mm}$ the approximately maximum torque is determined to $170\,\mathrm{N\,m}$, but normally the average (avg.) torque is lower. The maximum cadence is according to the literature set to $150\,\mathrm{min}^{-1}$. The cyclists crank torque is thereby not constant, it depends on the crank angle according Fig. 3, a detailed derivation of the cyclist torque is shown in [4]. The torque from the right pedal (blue) and the left pedal (green) sum up to the input torque. Therefore, the input torque from the test-bench has a variable torque set point with a frequency of the shown absolute sine wave set by the cyclist cadence below $3\,\mathrm{Hz}$. The drivetrains output

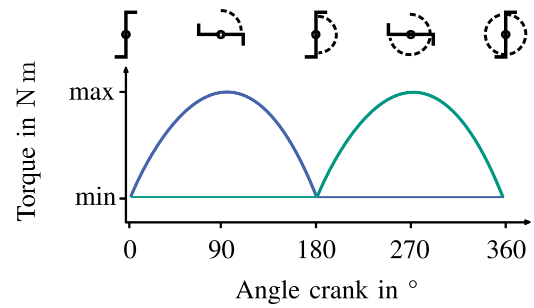

Fig. 3: Approximated input torque

chainring is linked to the rear gearshift. For this, revolution at the output of $380\,\mathrm{min}^{-1}$ is assumed, which enables also compatibility with S-Pedelecs with 29″ up to 26″ wheels. The maximum torque on the rear hub is determined as the sum of the cyclist and the drivetrain torque multiplied by the gear ratio. The resulting torque can be up to $400\,\mathrm{N\,m}$ in the lowest gear. In the test bench, it is limited to $200\,\mathrm{N\,m}$ to characterize the full torque range in medium gears whilst achieving high measurement precision. In addition to the torque, the test-bench must withstand the resulting chain force. The determined maximum values for the drivetrain input and output and the mechanical setup are listed in Tab. I.

TABLE I: Test-bench requirements

Dimension		**Value**
Cadence	max.	$150\,\mathrm{min}^{-1}$
Crank torque cyclist	max.	$170\,\mathrm{N\,m}$
	avg.	$50\,\mathrm{N\,m}$
Chain force	max.	$4\,\mathrm{kN}$
Revolutions rear wheel	max.	$380\,\mathrm{min}^{-1}$
Rear torque	max.	$200\,\mathrm{N\,m}$
	avg.	$80\,\mathrm{N\,m}$

IV. Test-Bench

The design of the test-bench is based on the power flow diagram from Fig. 2 and explained in detail in the following.

A. *Electrical drives*

The input drive is coupled to the bottom bracket axle of the drive unit and creates the input torque according to Fig. 3. The output drive is coupled to the rear hub and simulates the terrain, this is shown in Fig. 4. Both drives are permanent magnet synchronous motors (PMSM) with a gearbox of type *CMP71S* from SEW with a max. torque up to $192\,\mathrm{N\,m}$. Both drives are supplied and controlled by power electronics and a real-time signal processing system similar as described in [4].

B. Mechanical design

The schematic of the mechanical test-bench with the in- and output drives as well as the drive unit is shown in Fig. 4. The test-bench is designed to be adaptable for various drivetrains. For this, the input drive is mounted to a movable separate base plate, which allows to adjust the chain line for different DUT. Furthermore, the DUT can be rotated to simulate slopes for drive units with inclination sensors. The output drive is

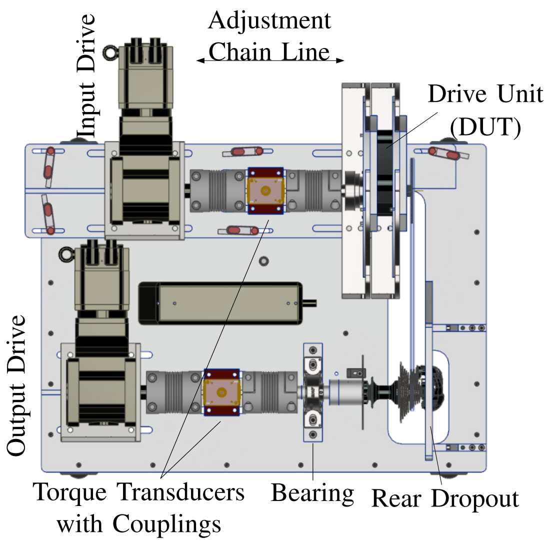

Fig. 4: Schematic of the test-bench

connected to the rear hub on disc side, utilizing the standard 6-bolts. This requires that the thru axle (red) has to be held in place by a bearing (blue), Fig. 5. Normally, the axle is tightened against the bicycle frame, which is not possible in this case. The forces transferred by the chain are partly held against by the right side with the hanger (SRAM UDH). For the left side a pillow block bearing (yellow) is used. The 11-speed rear derailleur is of type SLX from Shimano. The cassette is of type CS-M7000 with 11-42 teeth.

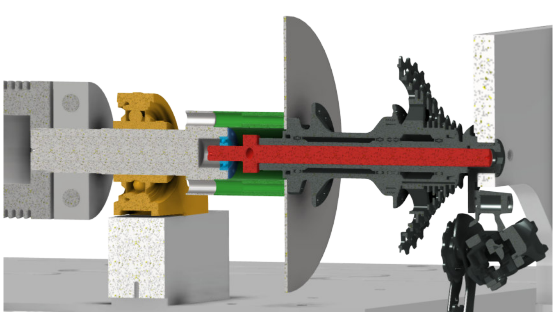
Fig. 5: Rear axle mount

C. Control design

Depending on the type of measurement routine, either the input drive is torque controlled and the output drive speed controlled or vice versa. For torque control, a current controller configured with the optimum amount is used. To achieve sinusoidal torques, a look-up table with the torque to current reference values is used. The speed controller is designed as cascaded speed control with an underlying current controller. The controls are implemented in the signal processing system with Matlab Simulink using code-generation.

D. Signal processing

For the speed and position measurement the drive integrated resolver of type RH1M from SEW, digitized with a resolution of $13\,\mathrm{bit}$, is used. The battery current sensor is of type *LA 100-P* from LEM. For the voltages, a passive voltage-divider is used. The input and output torque is measured by torque transducers from ETH of type DRVL and can be seen in Fig. 4. For the analog-digital conversion of the currents, the voltages, the torque and the temperature signals $15\,\mathrm{bit}$ AD-converters are available. Further details of signal processing hardware are described, e.g. in [9]. The test-bench can be operated with a LabVIEW interface. The LabVIEW interface is used to set up test routines and the settings of the data logging. For the post-processing of the measured data, the software Matlab is used.

V. Device-Under-Test

As device under test the drive unit of a commercial available GHOST pedelec type Kato 3 Hybrid (29″ size mountain bike) with a Shimano drive unit was investigated. The supported power modes of it are Eco, Trail and Boost. For the drivetrain

TABLE II: Device Under Test

Drive Unit	**Shimano STEPS DU-E8000**
Nominal power	$250\,\mathrm{W}$
Nominal torque	$70\,\mathrm{N\,m}$
Battery capacity	$504\,\mathrm{W\,h}$

testing, the pedelec drive unit is disassembled from the pedelec and mounted in the drivetrain test-bench. To control the drive unit peripherals like display, control unit and battery are necessary. Connectors, chain and derailleur are universal and part of the test-bench as explained in the previous section.

VI. Measurement Procedures

The aim of the test-bench is to characterize the drivetrain of a pedelec. The results can be used to parameterize a precise black box model of the drive unit for further developments. This requires various measurements, which are explained in this section. The measurements can be divided into stationary and dynamic measurements. To measure under realistic conditions a sinusoidal torque curve similar to a cyclists torque is induced, see section III, Fig. 3.

A. Stationary Measurement

The stationary measurements measure the reaction of the drive unit in certain situations. Thereby, the input parameters like torque and speed are set and adjusted until steady state is reached. These measurements are performed with different gears to characterize the behavior of the drive unit by different revolutions.

1) Characterization Measurements: For characterization of the drive unit, the reaction of it in different situation needs to be measured. For this purpose the driving speed, the cyclist's torque as well as the gear and driving mode needs to be changed systematically. The torque of the drive unit must be measured. For a full characterization, the entire power range of the cyclist must be covered in the procedure.

2) Long-range Measurements: In case of the R200 [1], speed, cadence and average torque are steady. The test run until the battery is depleted, as a result the achieved range is calculated and normalized to an assistance level of 200 %. With system test benches, tire losses are usually compensated by means of separate measurements. With the drivetrain test-bench, the absence of these losses simplifies the procedure and increases accuracy and reproducibility. The tire size however does not influence the result, as the gear is selected to achieve a specified speed and cadence. Any reasonable tire size can therefore be chosen for the calculation.

B. Dynamic Measurement

The response of the DUT to dynamic changes is crucial for the driving experience. In system test-benches, tire and roller both have high inertia, limiting the dynamics. Lacking those, the drivetrain test-bench achieves higher performance in this regard. In this paper, a constant braking torque is applied to the rear hub. To simulate acceleration, the cadence set point is abruptly changed from $0\,\mathrm{min}^{-1}$ to $60\,\mathrm{min}^{-1}$. The cyclist's torque is simulated to be limited, this limits the change in cadence and speed realistically.

VII. Measurement Results

Based on the presented measurement procedures, selected results are shown in this section.

A. Stationary Measurement

Varying the speed at the rear hub while an on average constant torque is applied to the bottom bracket axle gives results as shown in Fig. 6. The figure shows results in boost mode for different gears. In Fig. 6a, the measured electric power delivered by the battery is shown dependent on the speed. Fig. 6b shows the same data dependent on the cadence. It is evident, that in this mode, motor power at first rises with cadence, then remains almost constant up to a cadence of $100\,\mathrm{min}^{-1}$. After this it almost drops to zero, reaching what is presumably the highest supported cadence. The data implies, that the output torque in boost mode is independent of the speed. Speed only becomes relevant when the limit of $25\,\mathrm{km\,h}^{-1}$ is reached. This can be seen in Fig. 6b where the

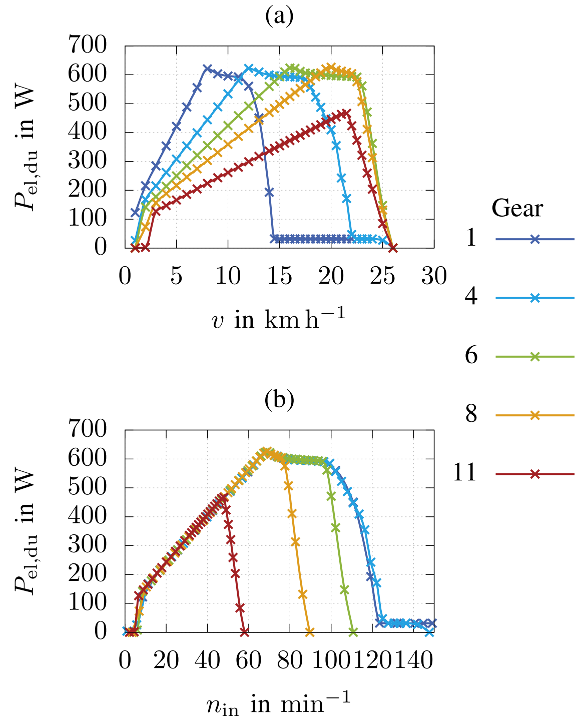

Fig. 6: Behavior of the DUT in boost mode for various gears

power curve over revolutions is equal for different gears until speed limit is reached.

Further analysis is done in 6. Gear, now the input torque is also varied. In Fig. 7a the interpolated data map for the eco-mode is shown. T_{du} is shown dependent of speed and T_{in}. The green plateau implies a limited output torque in this mode. Neither higher speeds nor higher input torque can increase the drive unit's output torque. Fig. 7b shows similar data for trail mode. In this mode, the cyclist is supported dynamically, meaning that higher cyclist torque results in higher support torque by the drive unit. Boost mode delivers the highest torque, clearly to be seen as yellow plateau in Fig. 7c. Only for low input torque or speed and high speeds, the torque is lower.

In addition to these characterizations, a long-range measurement is executed. The range according to [1] is determined to be around $R_{200} = 54\,\mathrm{km}$. This approximately matches previous measurement results with a system test bench [4].

B. Dynamic Measurement

Here, cadence is set to $60\,\mathrm{min}^{-1}$ at the time $0\,\mathrm{ms}$ which can be seen in Fig. 8. Due to mechanical effects, cadence rises starting from $100\,\mathrm{ms}$. The drive unit is legally allowed to support the cyclist at cadences above zero. It can be seen, that the electric power of the drive unit starts to rise at approximately $200\,\mathrm{ms}$. Therefore, the reaction time of the DUT is therefore considered to be around $100\,\mathrm{ms}$. The occurring oscillations in motor power suggest that the drive

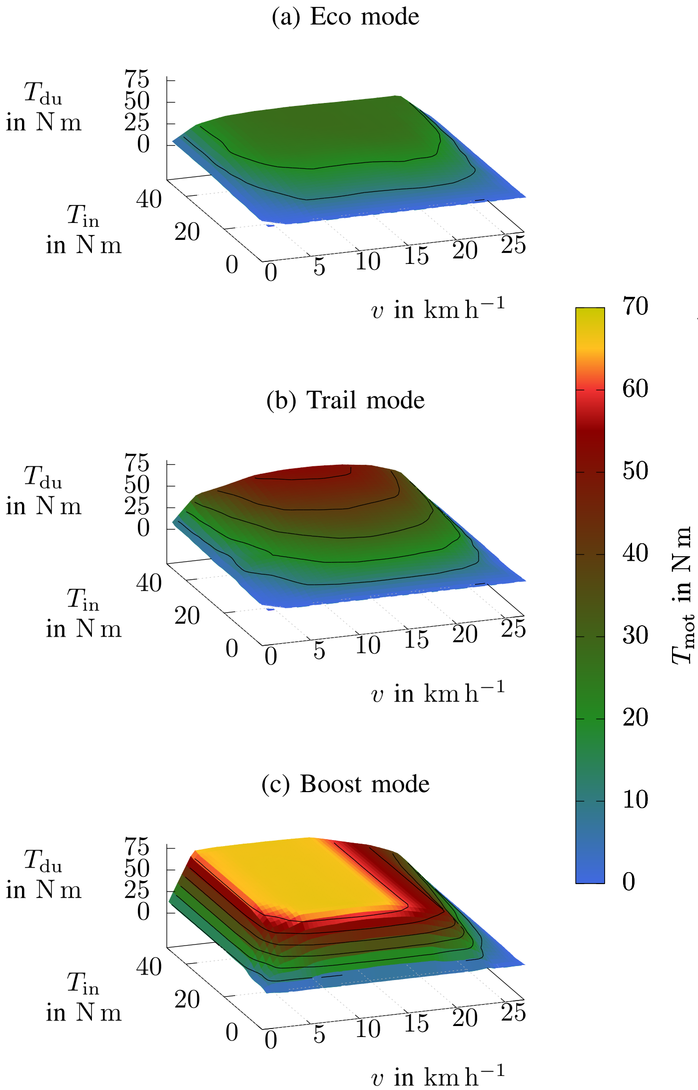

Fig. 7: Torque delivered by the DUT in different modes, depending on speed and cyclist torque

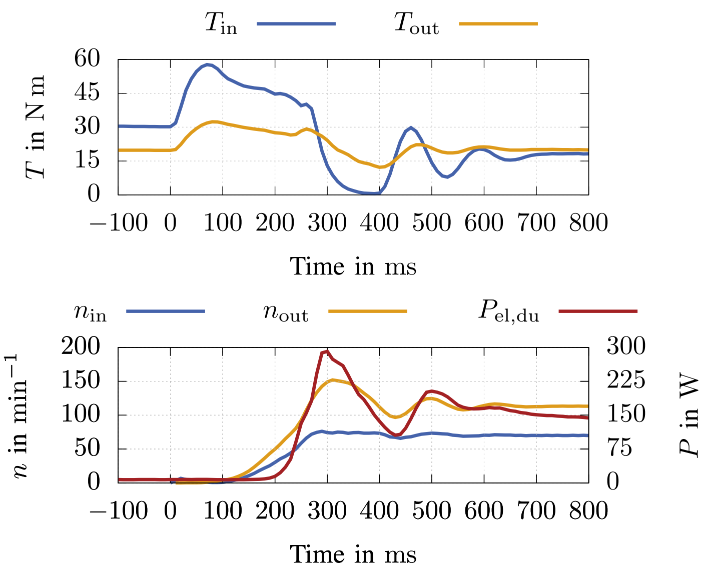

Fig. 8: Behavior of the DUT during acceleration in trail mode

unit is optimized for slower changes. This is also relevant for modelling and should be considered.

C. Comparison system test-bench and proposed drivetrain test-bench

For the comparison of both test-benches the focus is on the long-range measurement R200, the assistance level and a detailed view of the losses at both test-benches. This provides further information about the increased measurement accuracy of the new test-bench.

The results of the long range measurement R200 based on [1] lead to $R_{200} = 54\,\mathrm{km}$ by the proposed drivetrain test-bench and to $R_{200} = 52.4\,\mathrm{km}$ on the system test-bench. The deviation of $e = 1.6\,\mathrm{km}$ corresponds to approximately $3\,\%$. The deviation is very small, thus the results are comparable. An advantage of the R200 measurement is, that certain negative influences of the pedelec and the test-bench are compensated. A possible reason for the reachable distance, measured with the system test-bench being smaller than on the drivetrain test-bench, is given by losses that are not completely compensated. An almost compensated influence, for example, is the contact between the tire and the roll, which has a great impact on the accuracy.

Fig. 9 shows the result of the measurement of the fifth gear by on average constant torque and different velocities. The plots show the mechanical power at the output $P_{\mathrm{mec,out}}$, the losses of the drive unit $P_{\mathrm{loss,du}}$, the losses of the pedelec without drive unit $P_{\mathrm{loss,ped}}$ (including the tire) or $P_{\mathrm{loss,dt}}$ (excluding the tire), and the losses of the output of the respective test-bench $P_{\mathrm{loss,out}}$. Fig 9a is measured with the system test-bench. Fig 9b is measured with the new drivetrain test-bench. It can be seen, that the losses of the output at the system test-bench are large in comparison to the drivetrain test-bench. Similarly, $P_{\mathrm{loss,ped}}$ is larger than $P_{\mathrm{loss,dt}}$. Both is mostly explained by the friction in the contact between tire and roll, whereas the drivetrain test-bench has an almost frictionless contact at the output, like described in chapter IV. Further, not all the losses can be separated completely, and thus some have effects on the others, like the deformation of the pedelec frame. The comparison of the different losses shows, that the overall losses at the drivetrain test-bench are smaller. Thus, the accuracy of the different measurements is better, so more precise measurements can be performed.

To show the increased precision and accuracy of the measurements at the drivetrain test-bench, the assistance level is investigated. The assistance level is the relation between the torque of the drive unit and the torque of the cyclist. Fig. 6c shows, that the torque of the drive unit in boost mode is constant over the velocity and independent of the cyclist

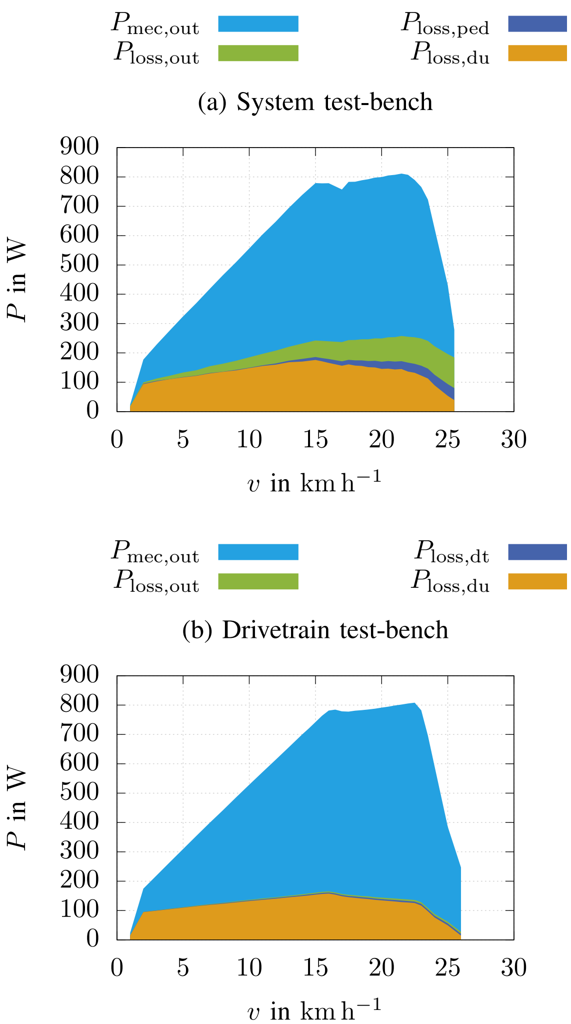

Fig. 9: Comparison between the test benches in terms of output energy and losses at constant torque and variable speed

torque. So if the cyclist torque is constant, a constant assistance level over speed is expected, like shown in Fig. 10. In red the result on the system test-bench is presented and in blue of the drivetrain test-bench. The blue curve is very smooth and the assistance level is constant as predicted. The red curve is similar with slight deviations. The reason for this is, that there are more uncertainties within the measurement, these result in more losses, like seen in Fig.9 and so in less precise results compared to the drivetrain test-bench.

VIII. Summary

In this paper, the development of a test-bench for pedelec drivetrains and the corresponding measurements are presented. Compared to state of the art pedelec full-system test-benches, the focus at this test-bench is only on the drivetrain. Because of this, more precise and extended measurements can be performed, parasitic effects do not interfere the results and also a better dynamic behavior is achievable. The results

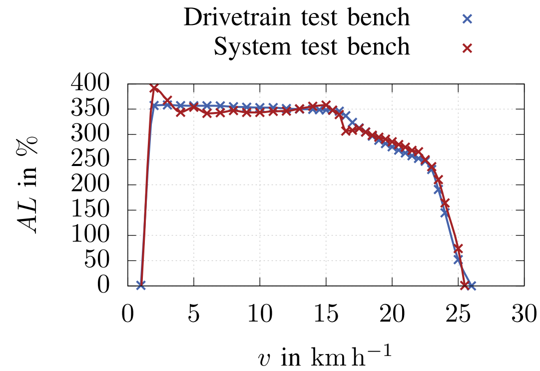

Fig. 10: Comparison of the determined assistance level for both test benches in an exemplary scenario in boost mode

allow a more precise parameterization of pedelec models for development and optimization of the drivetrain close to the reality. Further, a faster drive unit development will be possible. New control algorithms can be easily validated on precise models in an early stage and the standard testing of pedelecs is simplified.

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