

REAL-TIME DRIVER-IN-THE-LOOP SIMULATION FOR PEDELEC DRIVETRAIN TESTING: A DIGITAL TWIN APPROACH USING MATLAB/SIMULINK AND SPEEDGOAT HARDWARE

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ABSTRACT

This paper presents the development and implementation of a real-time Driver-in-the-Loop (DiL) simulation platform for pedelec drivetrain validation. The system architecture integrates a Digital Driver Twin—a biomechanical rider model executed on industrial SEW MOVI-C servo controllers—with a MATLAB/Simulink Real-Time environment running on Speedgoat target hardware. Deterministic Ethernet communication enables synchronized data exchange at 1 kHz sampling rates between the simulation host and distributed actuator nodes. The Digital Driver Twin generates physiologically realistic pedal torque profiles incorporating phase-shifted bilateral actuation and negative recovery torque components. Unlike conventional test approaches prescribing fixed trajectories, the proposed architecture enables emergent vehicle dynamics through closed-loop interaction between the virtual rider model, physical test specimen, and simulated environment. Experimental validation through 20,000 km endurance testing demonstrates the system's capability to reproduce field-representative failure modes unattainable with traditional constant-load protocols. The implementation showcases the convergence of industrial automation technology with model based design methodologies for advanced Hardware-in-the-Loop applications.

KEYWORDS

Real-Time Simulation, Driver-in-the-Loop, Digital Twin, MATLAB/Simulink Real Time, Speedgoat, Hardware-in-the-Loop, Industrial Ethernet, Pedelec Testing

1. INTRODUCTION

The increasing complexity of electrified vehicle drivetrains demands sophisticated testing methodologies that bridge the gap between numerical simulation and physical prototype validation. Real-time simulation platforms, particularly those implementing Driver-in-the-Loop (DiL) or Hardware-in-the-Loop (HiL) architectures, have become essential tools in automotive development cycles [1]. These systems enable the integration of virtual models with physical hardware components, facilitating comprehensive validation under controlled laboratory conditions while preserving the dynamic interactions characteristic of real-world operation.

The pedelec (Pedal Electric Cycle) market has experienced unprecedented growth, with annual production volumes exceeding 1.1 million units in Germany alone [2]. These electrically assisted bicycles operate as hybrid drivetrains where human pedaling effort is supplemented by motor assistance proportional to the rider's torque input. The European regulatory framework limits motor assistance to 250 W nominal power with speed cutoff at 25 km/h for standard pedelecs, or up to 4000 W peak power at 45 km/h for S-Pedelecs [3]. This regulatory context creates unique

testing requirements: the drivetrain must be validated under realistic human-machine interaction conditions rather than simplified constant load protocols.

The motivation for developing a real-time DiL simulation platform arises from documented discrepancies between field failures and laboratory test results. Micro-cracks, surface pitting, and progressive wear patterns observed in field-returned drive units differ fundamentally from damage patterns generated using conventional dynamometer testing. These field failures typically exhibit fatigue crack initiation at gear tooth roots under variable amplitude loading, bearing raceway pitting from cyclic Hertzian contact stresses, and chain wear patterns reflecting the characteristic torque reversals inherent to human pedaling biomechanics.

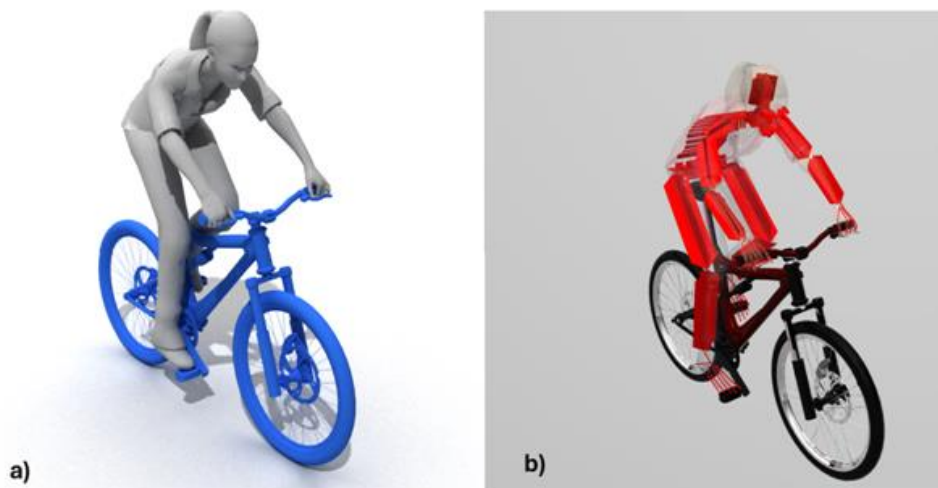


Figure 1. Biomechanical Driver Twin Concept: (a) Biomechanical Rider Simulation Skeleton Model providing bio-inspired input parameters, (b) anthropomorphic skeleton model defining kinematic constraints for torque profile generation.

The present work introduces a novel Driver-in-the-Loop simulation architecture implemented using MATLAB/Simulink Real-Time executing on Speedgoat target hardware, communicating via deterministic Ethernet protocols with SEW MOVI-C industrial servo controllers. The fundamental innovation lies in the Digital Driver Twin—a biomechanical rider model deployed directly within the SEW controller runtime environment (Fig. 1)—enabling microsecond-level torque command generation synchronized with the physical actuator control loops. This distributed architecture achieves the determinism required for realistic drivetrain interaction while leveraging the flexibility of model based design workflows.

2. REAL-TIME SIMULATION ARCHITECTURE

The proposed DiL simulation platform implements a hierarchical control architecture distributing computational tasks across multiple processing nodes according to their real-time requirements. This section describes the system topology, communication infrastructure, and the integration of the Digital Driver Twin within the industrial automation framework.

2.1. MATLAB/Simulink Real-Time Environment

The simulation host platform utilizes MATLAB/Simulink Real-Time (formerly xPC Target) executing on a Speedgoat Performance real-time target machine. The Speedgoat hardware features an Intel multi core processor with dedicated I/O modules providing deterministic data

Communication between the Speedgoat target and the host PC utilizes UDP/TCP protocols over a dedicated Ethernet connection, enabling real-time parameter adjustment and data streaming without interrupting model execution. A MATLAB-based graphical user interface (GUI) designated 'eBike Simulator' provides operator control including test configuration, live monitoring of 42 measured parameters, and emergency intervention capabilities.

2.2. Industrial Ethernet Communication

Deterministic communication between the Speedgoat real-time target and the SEW MOVI-C servo drive system is implemented using EtherCAT (Ethernet for Control Automation Technology). EtherCAT provides sub-microsecond synchronization across distributed nodes through its characteristic 'processing on the fly' architecture, where each node extracts and inserts data as frames traverse the network without store-and-forward delays [4]. The network topology comprises the Speedgoat master and three SEW MOVI-C slave nodes: two for pedal drive actuation (left/right) and one for load simulation (Fig. 2).

Process data objects (PDOs) exchanged each cycle include torque commands (master→slave), measured torques, encoder positions, motor temperatures, and diagnostic status (slave→master). The cycle time of 1 ms ensures that torque commands are updated synchronously with the biomechanical model execution on the Speedgoat, eliminating timing jitter that could compromise torque profile fidelity. Additionally, CAN bus communication interfaces the real-time system with the pedelec's internal electronics at 100 Hz, enabling bidirectional data exchange including pedal torque sensor readings, motor controller status, cadence, and temperature values.

2.3. Digital Driver Twin Implementation

The Digital Driver Twin represents the core innovation of the proposed architecture: a biomechanical rider model deployed within the SEW MOVI-C controller runtime environment using CODESYS, an IEC 61131-3 compliant programming framework. Unlike conventional approaches where torque trajectories are pre-computed and streamed to actuators, the Digital Driver Twin computes instantaneous torque commands locally at each control cycle based on real-time encoder feedback.

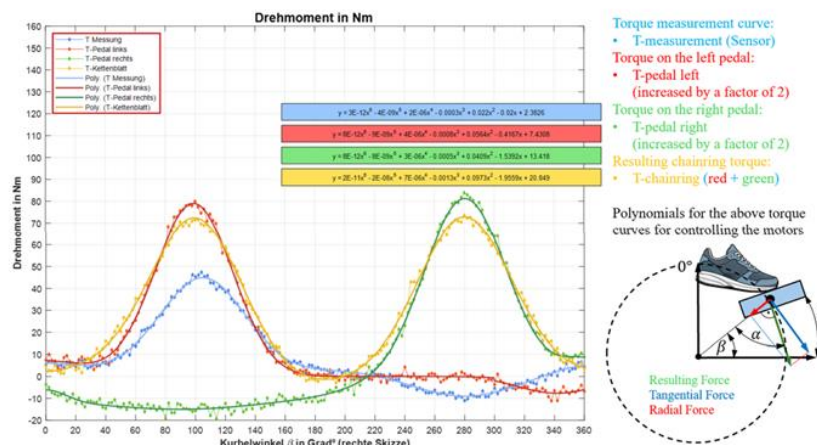


Figure 3. Biomechanical torque profiles generated by the Digital Driver Twin over one crank revolution. Left pedal (red), right pedal (green), resultant chainring torque (yellow), and measured torque (blue)

showing negative recovery phase. Polynomial approximations for real-time motor control shown as smoothed curves.

The biomechanical model generates separate torque profiles for left and right pedals as functions of crank angle β (Fig. 3). For the left pedal, the instantaneous torque is expressed as:

$$T_{pedal,L}(\beta) = T_{max} \cdot f_{prop}(\beta) + T_{neg} \cdot f_{rec}(\beta) \quad (1)$$

where $f_{prop}(\beta)$ is a Gaussian-shaped propulsion function peaking near 100° crank angle, and $f_{rec}(\beta)$ is a sigmoid-modulated recovery function generating negative torque between 195° and 360° as the recovering leg is lifted against gravity. The right pedal follows an identical profile with 180° phase offset, producing the characteristic dual-peak chainring torque observed in human pedaling biomechanics.

The Digital Driver Twin executes at 1 kHz within the SEW motion control task, synchronized via EtherCAT distributed clock to the Speedgoat master cycle. Torque scaling parameters (T_{max} , T_{neg}) are transmitted from the Simulink environment each cycle, enabling the higher-level rider motivation model to modulate pedaling intensity based on simulated riding conditions. This hierarchical architecture separates the computationally intensive environment simulation (Speedgoat/Simulink) from the time-critical torque generation (SEW/CODESYS), achieving both model flexibility and actuation determinism.

3. HARDWARE-IN-THE-LOOP TEST BENCH CONFIGURATION

The mechanical testbench integrates three primary functional subsystems: the pedal drive system simulating rider input, the load simulation system representing road resistance and vehicle inertia, and the instrumentation system for real-time data acquisition.

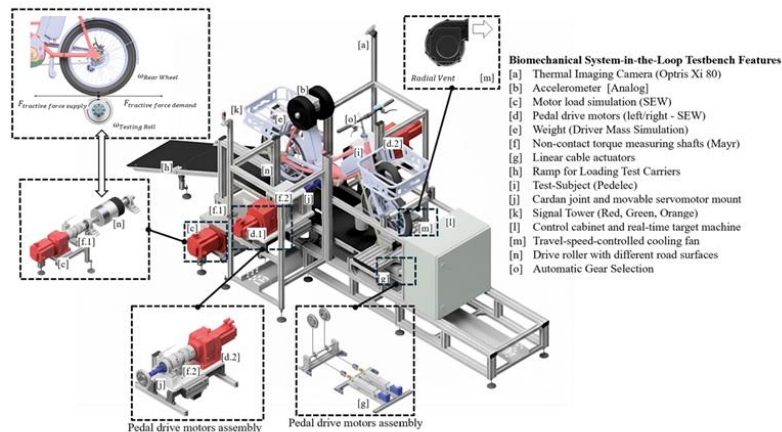


Figure 4. Isometric view of the Driver-in-the-Loop testbench identifying principal components: [a] thermal imaging camera, [b] accelerometer, [c] load simulation motor (SEW), [d.1/d.2] pedal drive motors (SEW), [e] rider mass simulation, [f.1/f.2] Mayr torque measuring shafts, [g] linear cable actuators for Wiegetritt simulation, [h] cardan joint assembly, [i] signal tower, [l] control cabinet with Speedgoat real-time target, [m] speed-controlled cooling fan, [n] testing roller, [o] automatic gear selection servo.

3.1. Actuation Hardware

Two SEW synchronous servo motors independently actuate the left and right pedal cranks (Fig. 4,

[d.1/d.2]), rated for peak torques of 665 Nm with gear reduction ratio 23.44:1. This specification provides sufficient bandwidth to reproduce dynamic torque variations at cadences up to 120 rpm. The load simulation motor (SEW, 425 Nm nominal, [c]) drives the rear wheel contact roller, functioning as a controllable brake or regenerative drive source. Non-contact torque measuring shafts (Mayr, [f.1/f.2]) positioned between each motor and the corresponding crank provide real-time torque feedback with measurement uncertainty below 0.1% of full scale. Linear cable actuators [g] replicate standing pedaling ('Wiegetritt') radial loads, applying alternating vertical forces up to 500 N synchronized with pedal position via RS485 communication at 50 Hz.

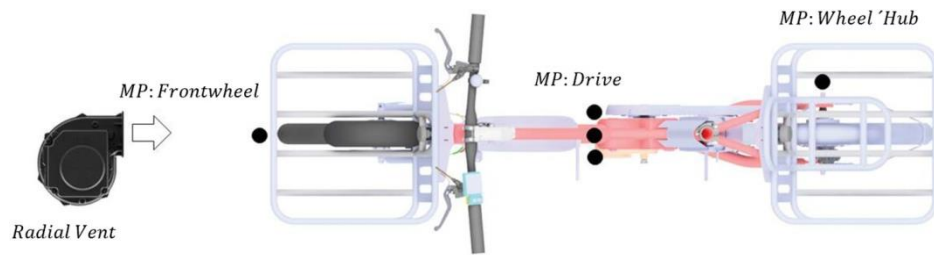


Figure 5. Schematic experimental setup of the cargo pedelec test specimen showing measurement point locations (MP: Frontwheel, Drive, Wheel Hub) and radial ventilation system for speed-dependent thermal management.

3.2. Test Specimen Integration

The test specimen—a complete pedelec (Fig. 5)—mounts within the testbench frame using adjustable pillar supports with spring tensioners maintaining tire contact with the rollers. The spring tensioners are compression springs integrated into the vertical support pillars that apply constant downward preload force (approximately 200 N), ensuring consistent contact pressure throughout dynamic testing. The pedelec's original battery is substituted with a laboratory power supply (Elektro-Automatik PSI-8080 60 T), enabling precise measurement of electrical power consumption.

Three primary measurement points (MP) are installed on the test specimen for multi-point thermal and kinematic characterization. A radial ventilation system generates velocity-proportional forced convection at the drive unit housing to replicate aerodynamic cooling conditions encountered during field operation, with airflow velocity modulated proportionally to simulated vehicle speed.

4. EXPERIMENTAL VALIDATION

The DiL simulation platform was validated through an extensive endurance test campaign conducted between February and July 2021. Testing accumulated a total distance of 20,007 km over 1,559 hours of continuous operation.

4.1. Real-Time Performance Metrics

The validation process comprised three stages: (1) static calibration verifying torque sensor accuracy against traceable reference standards, (2) dynamic validation comparing commanded versus measured torque profiles, and (3) long-term stability assessment monitoring control performance throughout the 20,000 km campaign. Closed-loop torque tracking demonstrated accuracy within $\pm 2\%$ across the operating range. The EtherCAT communication achieved 100% frame delivery with maximum jitter below 50 μs , confirming the determinism required for

biomechanical profile reproduction. The Speedgoat target maintained CPU utilization below 60% during continuous operation, providing headroom for model complexity expansion.

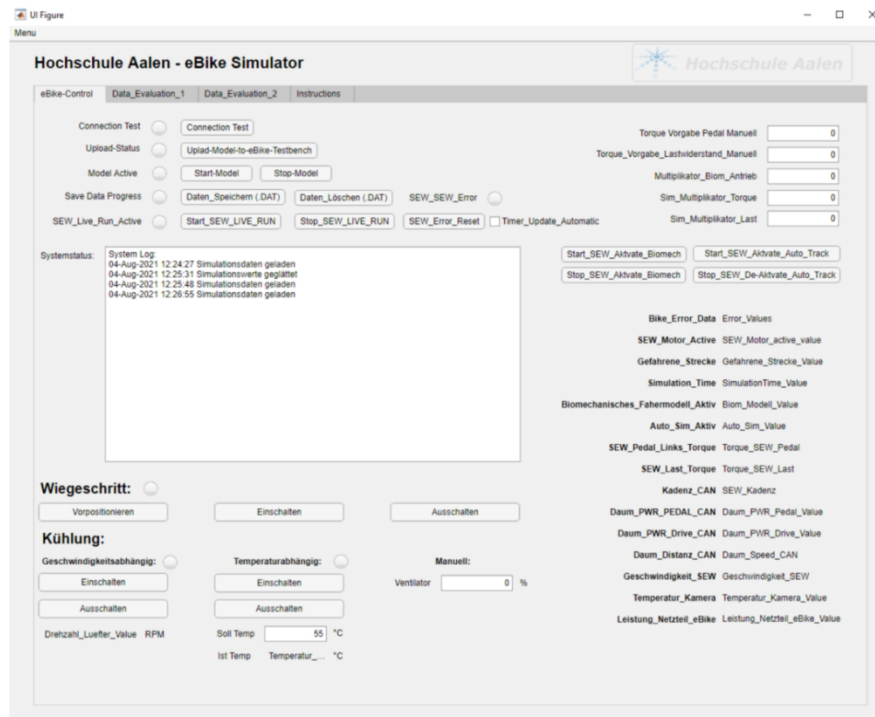


Figure 6. MATLAB-based 'eBike Simulator' graphical user interface for real-time test bench operation. The interface provides connection management to Speedgoat target, drive control, manual parameter input, biomechanical model activation, real-time status monitoring of 42 parameters, Wiegetritt control, and thermal management system interface.

4.2. Human-Machine Interface

Test bench operation is controlled through the MATLAB-based 'eBike Simulator' GUI (Fig. 6) communicating with the Speedgoat real-time target via UDP/TCP protocols. The interface provides comprehensive control and monitoring capabilities including: connection test and model upload to Speedgoat target, SEW drive activation control, real-time parameter adjustment (torque setpoints, scaling multipliers), biomechanical model and automatic track activation, and continuous display of system status including fault codes, distances, torques, CAN data, temperatures, and power consumption.

4.3. Field-Representative Failure Reproduction

The extended test campaign produced several component failures providing insight into realistic damage mechanisms: hub gear slipping (1,822 km), chain guard fracture (2,623 km), chain fracture (7,908 km, 15,660 km), and rear hub bearing pitting (8,104 km, 17,604 km). Significantly, the central drive unit—the primary test object—exhibited no functional failures throughout the campaign, demonstrating robust design margins for the tested load collective.

The observed failure modes correspond closely to patterns documented in field returns, validating the hypothesis that biomechanically realistic loading reproduces damage mechanisms unattainable with constant-load protocols. The temporal correlation between load events—acceleration sequences, torque reversals, and standing pedaling episodes—appears essential for

replicating field-representative fatigue accumulation.

5. DISCUSSION

The proposed DiL simulation architecture demonstrates the feasibility of integrating model-based design methodologies with industrial automation infrastructure for advanced HiL applications. The hierarchical distribution of computational tasks—environment simulation on Speedgoat/Simulink, biomechanical torque generation on SEW/CODESYS—achieves both flexibility and determinism by matching algorithm complexity to platform capabilities.

The Digital Driver Twin concept extends traditional HiL approaches by embedding domain-specific models within actuator controllers rather than centralizing all computations on the simulation host. This distributed architecture reduces communication bandwidth requirements, improves timing determinism, and enables actuator-local safety supervision. The approach generalizes to other applications requiring synchronized multi-axis actuation with complex trajectory generation.

The MATLAB/Simulink workflow provided significant development efficiency advantages. Model based design enabled rapid iteration between simulation and deployment, while Simulink Real-Time's integration with Speedgoat hardware minimized commissioning effort. The ability to modify environment models, logging configurations, and safety parameters without recompiling the SEW controller code accelerated test protocol development.

6. CONCLUSIONS

This paper presented a real-time Driver-in-the-Loop simulation platform for pedelec drivetrain validation, integrating MATLAB/Simulink Real-Time on Speedgoat hardware with SEW MOVIC industrial servo controllers via deterministic Ethernet communication. The key innovation—the Digital Driver Twin—embeds a biomechanical rider model within the actuator controller runtime, enabling microsecond-level torque generation synchronized to the motion control loop.

Experimental validation through 20,000 km endurance testing demonstrated $\pm 2\%$ torque tracking accuracy, 100% EtherCAT frame delivery, and reproduction of field-representative failure modes including bearing pitting and chain wear. The architecture successfully bridges model-based design workflows with industrial automation technology, demonstrating that Digital Twin concepts can be practically deployed in demanding real-time applications.

Future work will extend the platform to incorporate AI-based predictive maintenance algorithms, three dimensional radial loading simulation, and musculoskeletal rider models for enhanced biomechanical fidelity. The testbench is operational at Hochschule Aalen and available for collaborative drivetrain development programs.

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