

TWDM

AiP

Vehicle-Level Testing with
Steering Capability



Executive Summary

Rising Complexity in Vehicle Development

Modern vehicle development is increasingly defined by rising system complexity, driven by electrification, software-defined architectures, and advanced driver assistance systems. As interactions between subsystems grow, validation and integration efforts increase significantly.

Limitations of Conventional Testing

Conventional testing approaches, particularly proving ground and road testing, offer high realism but are limited in reproducibility, scalability, and efficiency. This creates a need to shift validation activities into controlled laboratory environments.

TWDM as a Vehicle-Level Functional Test Platform

The Torque Wheel Dynamometer (TWDM) enables vehicle-level functional testing under laboratory conditions. By applying torque directly at the wheel while maintaining full steering capability, it allows realistic investigation of system interaction and vehicle behavior.

Position within the Development Landscape

Positioned between chassis dynamometers, powertrain integration test benches, and proving ground testing, the TWDM complements existing validation approaches. It enables early and reproducible testing of integrated vehicle functions, reducing reliance on road testing.

Integration into Existing Toolchains

The TWDM integrates seamlessly into established simulation environments such as Vehicle-in-the-Loop systems. It connects virtual driving scenarios with real vehicle behavior, enabling hybrid validation without changing existing workflows.



Scalable and Application-Driven Concept

With its compact design and scalable performance classes, the TWDM supports a wide range of applications—from early functional validation to high-dynamic ADAS and energy flow testing.

Impact on Development Efficiency

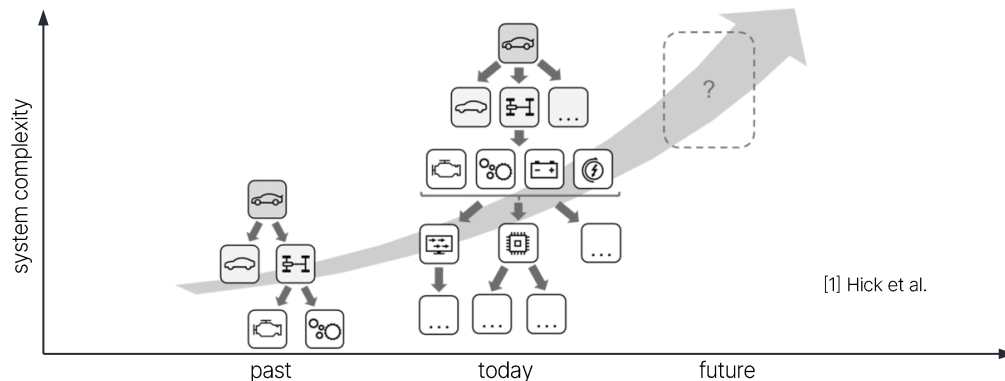
By shifting validation upstream, the TWDM reduces test effort, shortens development cycles, and enables more efficient and systematic validation of modern vehicle systems.

Introduction

Rising Complexity Demands New Testing Approaches

The development of modern vehicles is undergoing a fundamental transformation driven by electrification, software-defined architectures, and the rapid expansion of advanced driver assistance systems (ADAS). As vehicle functions become increasingly interconnected, the number of interactions between powertrain, vehicle dynamics, E/E systems, and software grows significantly. Vehicle behavior is increasingly defined by system interaction rather than individual components.

As a result, the required effort for validation, calibration, and system integration increases continuously, challenging traditional development and testing approaches.



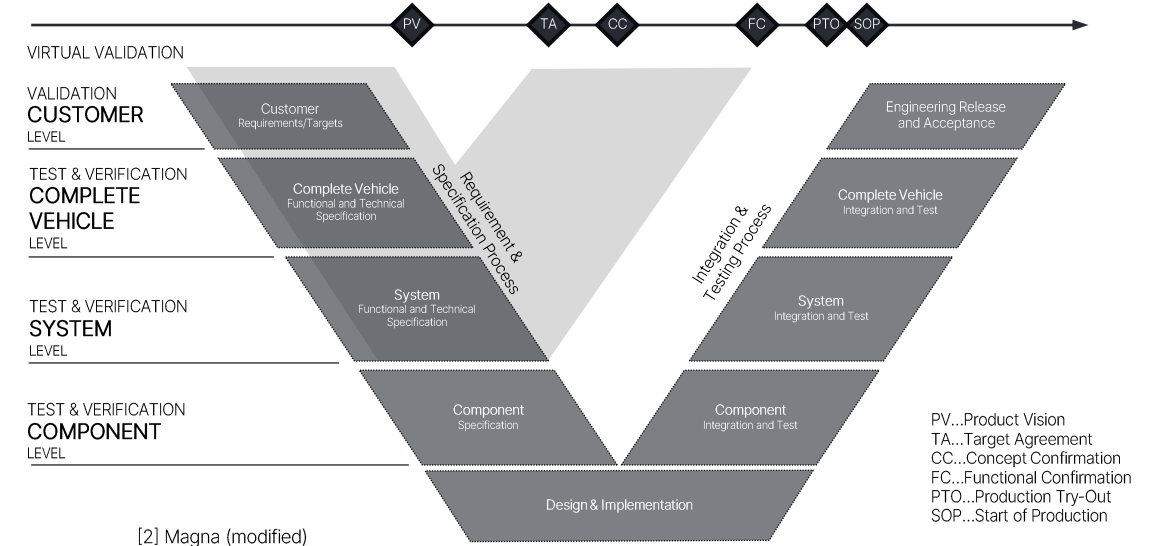
From Challenges and Limitations to Controlled Environments

At the same time, modern vehicle functions must be validated across a wide range of scenarios, including safety-critical and rare events. Conventional proving ground and road testing offer high fidelity but are limited in terms of reproducibility, scalability, and efficiency.

This drives the shift toward integrated validation environments combining simulation, hardware, and vehicle-level testing.

These approaches enable:

- reproducible execution of complex scenarios
- early validation of system interactions
- reduced dependency on physical test tracks



Bringing Vehicle Behavior into the Laboratory

While simulation-based development and system-level test benches have significantly advanced, a gap remains at vehicle level: the ability to evaluate functional behavior under realistic interaction conditions, including steering and combined driver inputs.

Vehicle-level functional test benches address this gap by enabling real vehicle testing under controlled conditions, bridging the space between simulation and proving ground validation.

Positioning of TWDM in Modern Development

In this context, the TWDM provides a compact and flexible solution for vehicle-level functional testing.

By combining torque-controlled wheel excitation with steering capability, the TWDM enables testing of vehicle behavior under realistic conditions within a laboratory environment. This makes it possible to bring critical validation tasks, traditionally performed on proving grounds, into earlier development phases.

[1] Hick, H., Bajzek, M. & Faustmann, C. Definition of a system model for model-based development. SN Appl. Sci. 1, 1074 (2019).

<https://doi.org/10.1007/s42452-019-1069-0>

[2] <https://www.magna.com/de/stories/inside-automotive/2022/die-grundlagen-des-fahrzeugentwicklungsprozesses>

Concept & Principle

Fundamental Architecture and Operating Principle

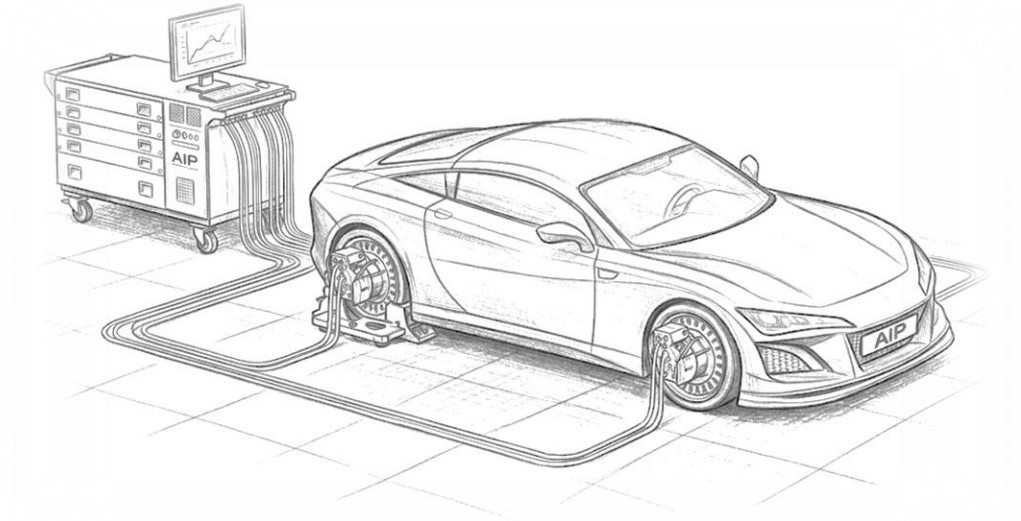
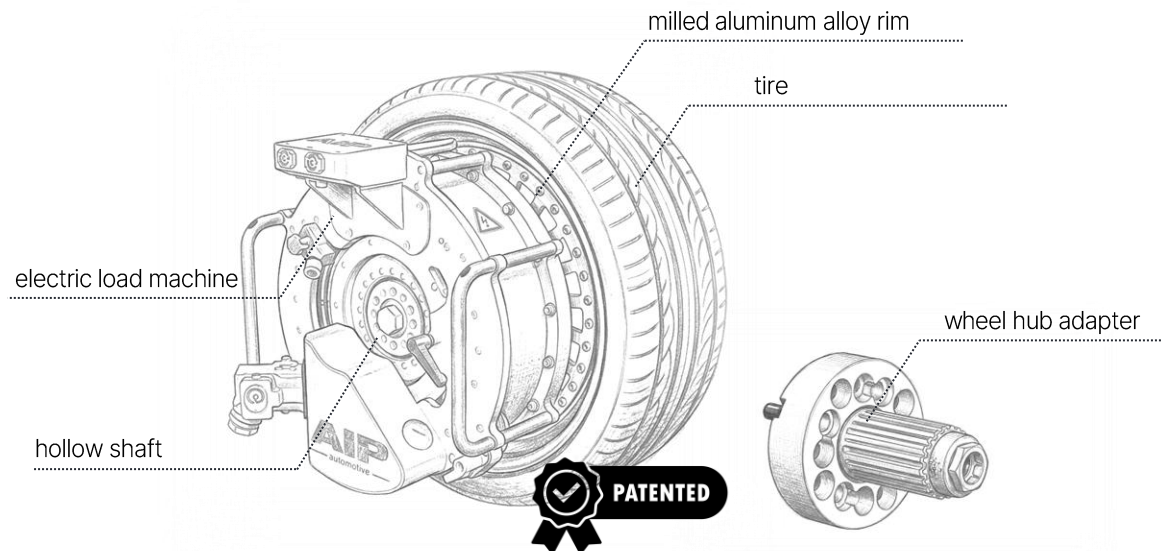


Full-Vehicle Testing Focused on Early Development Phases

The Torque Wheel Dynamometer (TWDM) is a compact full-vehicle test bench designed to support early and iterative testing in modern vehicle development processes. Similar to other advanced test bench concepts such as R2R or conventional powertrain testbenches, the TWDM enables engineers to validate vehicle functions, system interactions, and operating strategies long before extensive proving ground testing becomes necessary. Its primary objective is to shift relevant test content as early as possible into a controlled, repeatable laboratory environment.

Torque-at-the-Wheel as Core Operating Principle

The fundamental concept of the TWDM is based on applying road loads directly at the wheel level. Electrically driven load machines are integrated into AIP's patented drive-through rim, forming the core of the TWDM concept and enabling direct torque application at wheel level. Each wheel can be controlled individually in torque, speed, or road load simulation mode, enabling precise replication of longitudinal vehicle dynamics without mechanical intermediates between vehicle and load generation.



Compact Design with Minimal Infrastructure

A distinguishing feature of the TWDM is its exceptionally compact and infrastructure-efficient design. Depending on the performance class, the system can be operated with air cooling or optionally with liquid cooling supported by an external chiller. In contrast to steerable roller systems or flat-belt dynamometers, no underfloor pit or extensive structural modifications are required. This significantly reduces installation effort, cost, and space requirements while maintaining full functionality as a complete vehicle test bench.

True Steering Capability During Test Operation

Unlike high-power roller-based systems or R2R configurations, which typically offer limited or no steering capability, the TWDM allows the vehicle to remain fully steerable during operation. This enables test scenarios that combine longitudinal dynamics with steering inputs, making the system particularly suitable for applications such as ADAS, vehicle-in-the-loop testing, and E/E architecture development.

Complementing Proving Grounds and High-Power Test Benches

The TWDM does not aim to replace conventional powertrain testbenches, chassis dynamometers or proving ground testing. Instead, it represents a missing link between classical roller test benches and advanced high-power systems, focusing on compactness, steering capability, and system accessibility. By enabling a large portion of functional testing and calibration to be performed in the laboratory, the TWDM contributes to a significant reduction of test time, test mileage, and complexity during later proving ground phases.

Steering Motion Emulation (SME)

Controlled Steering Interaction at Vehicle Level

Extending Vehicle-Level Testing with Steering Interaction

The Steering Motion Emulation (SME) introduces controlled steering as an active test dimension, complementing torque-based vehicle excitation.

By combining torque-controlled wheel excitation with a dedicated turntable system beneath the steered wheels, the SME enables simultaneous driving and steering tests.

Turntable-Based Steering Interface

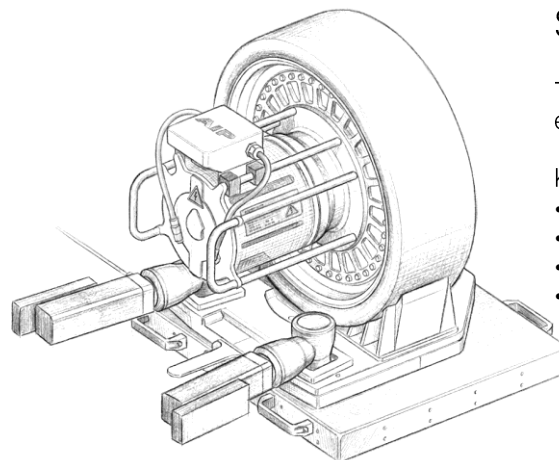
At the core of the SME concept are turntable-mounted wheel interfaces installed beneath the steered wheels of the vehicle.

These turntables:

- enable low-friction and unrestricted steering motion
- compensate for geometric displacement of the wheel contact point
- maintain consistent tire-ground interaction during steering maneuvers

This ensures realistic kinematic behavior, even under dynamic steering conditions.

Depending on the configuration, the SME system can operate either as a pure steering angle measurement system (SAM) or as an active steering emulation system with controlled torque feedback (ATF).

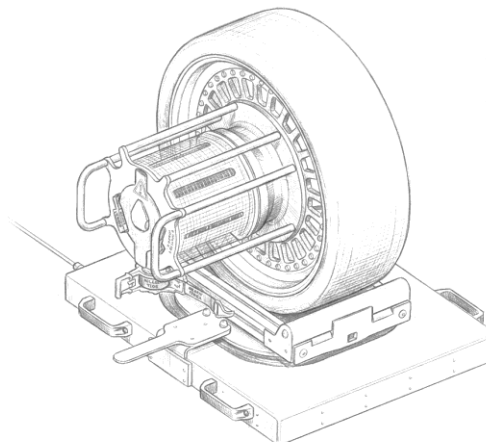


SME-SAM – Steering Angle Measurement

The SME-SAM configuration enables precise measurement of steering motion without applying active forces.

Key characteristics:

- high-resolution steering angle measurement
- optical absolute angle sensing
- compensation of contact point displacement
- suitable for observation-based validation



SME-ATF – Active Torque Feedback

The SME-ATF configuration extends the system with active steering torque feedback, enabling realistic emulation of steering loads.

Key characteristics:

- application of controlled steering torque (up to significant levels)
- closed-loop real-time control via RTCU
- integration of simulation inputs (e.g. CarMaker, dSPACE)
- reproduction of real steering feel and system response

System Comparison & Key Differentiators

Selecting the Right Vehicle Test Bench Concept

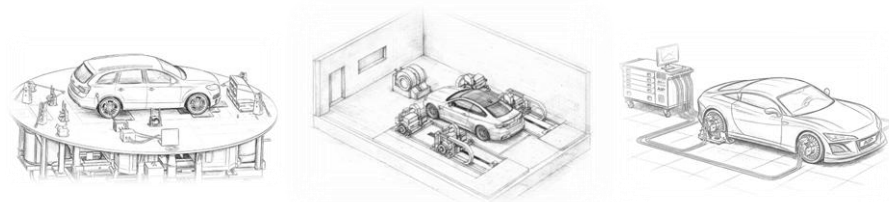


Complementary Test Bench Concepts in Vehicle Development

Vehicle development relies on a range of test bench concepts, each optimized for specific validation tasks. Chassis dynamometers, powertrain test benches such as ATS or R2R, and compact vehicle-level functional test benches represent complementary approaches rather than competing solutions.

Their differentiation is defined by system focus, steering capability, infrastructure requirements, and the type of validation tasks they enable.

Comparison of Full Vehicle Test Bench Concepts



	Chassis Dynamometer	ATS / R2R	TWDM
System focus	Emissions, durability, performance	Powertrain integration & energy flow	Vehicle-level functional behavior and validation
Typical Application	Homologation, endurance	Power measurement, efficiency, thermal	ADAS, VIL, E/E, energy flow, functional tests
Steering capability	Limited	Limited	Full steering capability
Power range	High	Very high	Moderate (application-specific)
Infrastructure	High (pit, fixed installation)	Medium to high	Low (no pit, compact, mobile)
Test flexibility	Limited by setup	Focused on drivetrain	High (multi-domain applications)
Development phase	Mid-late	Early-mid (system integration)	Early-mid (functional validation)

Simultaneous Steering and Driving in the Laboratory

A defining feature of the TWDM is the ability to combine drive excitation with steering input under controlled laboratory conditions. This enables test scenarios that cannot be executed on conventional powertrain or chassis dynamometers, such as combined longitudinal-lateral vehicle behavior, ADAS maneuvers, and driver interaction testing.

Compact and Infrastructure-Efficient Design

The TWDM requires no underfloor pit, no large structural modifications, and no chassis fixation, resulting in significantly reduced installation effort and cost. Its compact and mobile design enables flexible deployment across different test environments.

Full Vehicle Accessibility for Functional Testing

Unlike roller-based or enclosed systems, the TWDM provides unrestricted access to the vehicle, enabling:

- ADAS sensor stimulation
- E/E system integration
- external measurement equipment

This open setup is particularly relevant for modern software-defined vehicle functions.

Focused on Functional and Interaction-Driven Testing

While ATS and R2R systems are optimized for powertrain integration, high load operation, and energy flow validation, the TWDM is specifically tailored to vehicle-level functional validation. This includes system interaction, control strategy behavior, and the influence of steering and driver input on vehicle dynamics.

Complementing – Not Replacing – Existing Test Systems

The TWDM does not replace chassis dynamometers, ATS, or proving ground testing. Instead, it complements them by shifting functional validation and system interaction testing into the laboratory, reducing downstream test effort and iteration cycles.

TWDM in the Vehicle Development Workflow

Vehicle-Level Functional Testing Under Laboratory Conditions

Role of Vehicle-Level Functional Test Benches

Vehicle-level functional test benches are used to evaluate the behavior of a fully integrated vehicle in a controlled laboratory environment. Their purpose is not to replace component- or system-level testing, nor to substitute proving ground validation, but to close the gap between these stages by enabling early verification and interaction testing at vehicle level.

In modern development processes, such test environments serve as a key element for reducing iteration loops, identifying integration issues early, and stabilizing vehicle behavior before extensive road testing is performed.

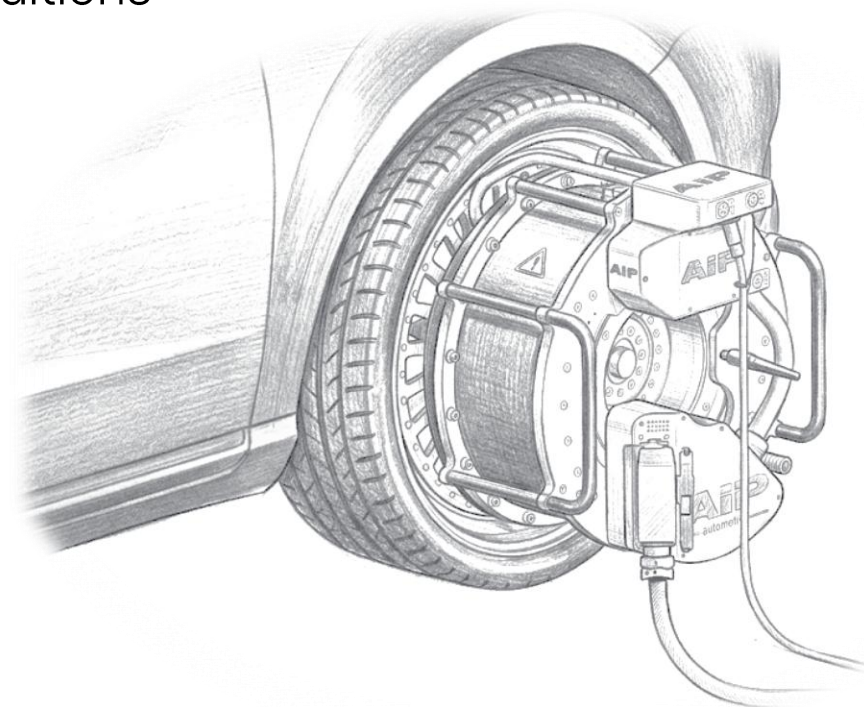
TWDM Usage in Mid Development Phases

The TWDM is typically applied after major components and subsystems have reached a sufficient level of maturity, while functional concepts, control strategies, and system interactions are still subject to iteration. In this phase, the vehicle represents an integrated system, but changes can still be implemented efficiently.

Within this development window, ATS and R2R systems are frequently the tools of choice for integrated powertrain validation. They enable system-level investigations of complete drivetrains, energy flows, thermal behavior, and efficiency under high load conditions. The TWDM complements these systems by addressing system integration from a vehicle-function perspective rather than a power-centric one.

Steering Capability as a Differentiating Functional Degree of Freedom

The availability of steering capability during test operation fundamentally changes the scope of functional questions that can be addressed in the laboratory. With steering input available, testing extends beyond purely longitudinal excitation to include combined driver actions, assisted maneuvers, and the interaction of longitudinal and lateral control functions.



This enables functional validation tasks that are difficult or inefficient to perform on powertrain-focused system integration benches, such as ADAS maneuvers, Vehicle-in-the-Loop scenarios, or interaction testing between driver input, automation functions, and vehicle dynamics. In this context, the TWDM expands the system integration landscape by adding functional and interaction-focused degrees of freedom at vehicle level.

Impact on Proving Ground Utilization

The TWDM does not replace ATS, R2R, or proving ground testing. Instead, it complements them by relocating functional exploration, calibration iteration, and system interaction analysis into an early laboratory phase. As a result, proving ground activities can focus more strongly on validation and boundary condition testing rather than discovery and troubleshooting.

This upstream shift reduces the number of required iterations, vehicle kilometers, and test dependencies, contributing to a more efficient and predictable overall vehicle development process.

Application Domains and Performance Classes

Vehicle-Level Functional Testing Across Multiple Development Domains



From a Single Test Bench to Multiple Use Cases

The TWDM supports a wide range of vehicle-level functional validation tasks, independent of the specific system configuration. All application domains are based on the ability to evaluate vehicle behavior under controlled conditions including steering interaction and system coupling.



ADAS and Active Safety Validation

Validation of driver assistance systems under reproducible conditions, including Vehicle-in-the-Loop scenarios and interaction between driver input and automation functions.



E/E System Interaction Validation

Investigation of cross-domain system behavior, communication timing, and interaction in distributed and centralized vehicle architectures.



Energy Flow and Range Validation

Evaluation of efficiency and energy consumption, including the influence of steering and system interaction on overall vehicle behavior.



Powertrain Functional Validation

Validation of drivability, operating strategies, and system interaction within defined operating ranges.



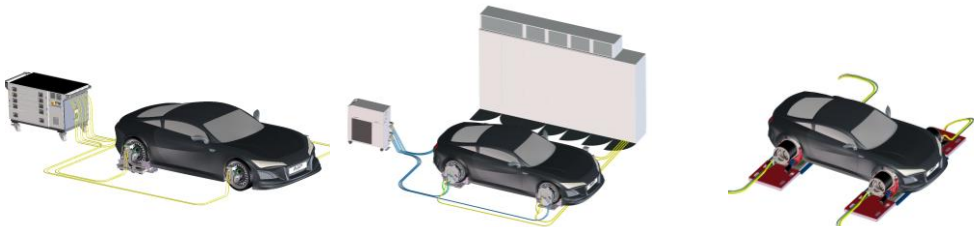
Pre-Validation and Regulatory Testing

Execution of reproducible test scenarios supporting RDE-related scenarios, NCAP, and certification-related preparation.

Adaptable System Concept for Varying Performance Requirements

The TWDM is designed as a modular and scalable test bench concept. Different configurations can be selected depending on the required dynamic performance and power level.

Performance classes define the capability to execute validation tasks, independent of the application domain. This enables precise alignment of the system with use cases ranging from early functional validation to high-dynamic ADAS and energy flow scenarios.



	Air-cooled	Water-cooled	HighPerformance
max. Power* [kW]	20	75	280
max. Torque* [Nm]	332	1600	3000
max. Speed* [rpm]	850	1800	2000
Application	early functional validation E/E system interaction validation EMC testing	extended functional validation drivability and system behavior energy flow and range testing	high-dynamic ADAS validation VIL scenarios (NCAP, GSR) energy flow and range testing
* per wheel	Early-stage validation with minimal infrastructure and maximum flexibility	Expanded operating range for system integration and realistic driving conditions	High-dynamic testing for advanced vehicle functions and energy-related investigations

Integration into Simulation-Based Development Environments

Seamless Coupling of TWDM with Road Load Simulation and VIL Toolchains

TWDM as Part of a Closed-Loop Validation Environment

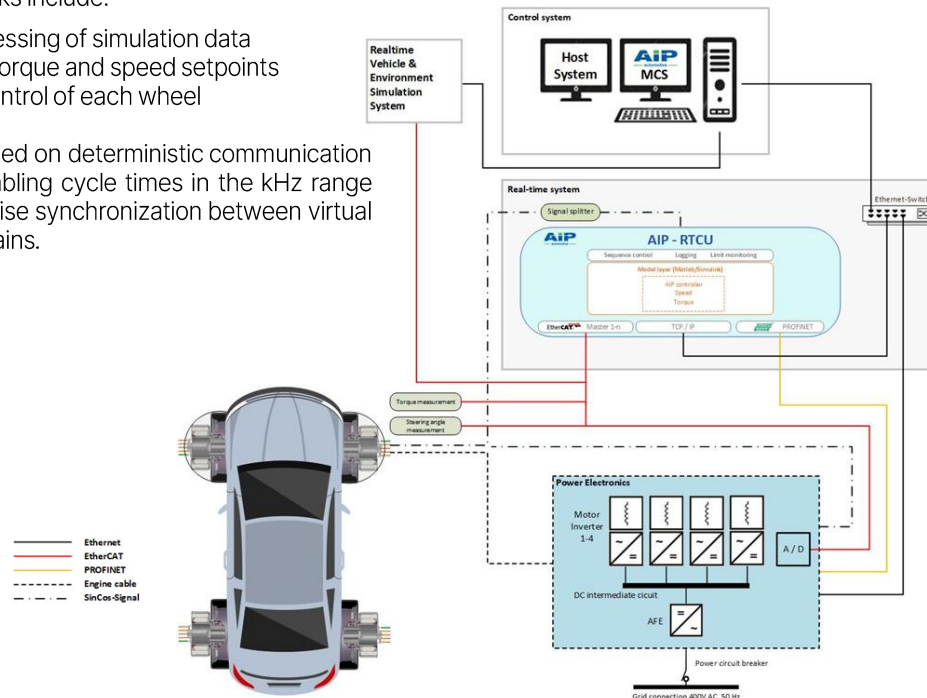
Modern vehicle development relies on simulation environments such as IPG CarMaker, dSPACE ASM, or similar real-time solutions to represent vehicle behavior, road conditions, and traffic scenarios. The TWDM is designed to integrate directly into these existing environments as part of a closed-loop Vehicle-in-the-Loop (VIL) architecture. In this setup, simulation and physical test bench operate as a unified system, where virtual scenarios are executed through real vehicle hardware.

Real-Time Execution via the AiP Control System

The AiP Real-Time Control Unit (RTCU) acts as the central interface between simulation and test bench hardware. Key tasks include:

- real-time processing of simulation data
- generation of torque and speed setpoints
- closed-loop control of each wheel

The system is based on deterministic communication via EtherCAT, enabling cycle times in the kHz range and ensuring precise synchronization between virtual and physical domains.



Transformation into Physical Vehicle Behavior

The TWDM converts simulation outputs into real physical interaction at the vehicle:

- torque is applied directly at each wheel
- steering inputs are executed via the real vehicle system
- vehicle response is generated by actual mechanical and electrical behavior

Measured signals such as:

- wheel speeds
- Torque
- steering interaction (optional)

are fed back into the simulation, closing the loop.

Seamless Integration into Existing Toolchains

A key advantage of the TWDM concept is its compatibility with existing development environments. Customers can reuse:

- established simulation toolchains
- existing test scenarios
- validated vehicle models

without fundamental changes to their workflow. The TWDM extends these environments by adding a physical execution layer, enabling the transition from purely virtual to hybrid validation.

The modular control concept allows integration at different levels:

- via EtherCAT into real-time simulation systems
- via Ethernet or fieldbus interfaces into laboratory automation systems
- via MCS as standalone or supervisory control layer

This flexibility allows adaptation to a wide range of customer architectures.

A silver car is shown in a laboratory setting, equipped with various sensors and mechanical components for testing. The car is positioned on a test rig, and its front end is illuminated. The background shows the industrial structure of the lab.

From torque to steering

enabling real vehicle behavior in the lab.

AiP

Sebastian Schurl

Product Management

sebastian.schurl@aip-automotive.de

AIP GmbH & Co. KG

Hoyen 30 | 87490 Haldenwang | Germany

+49 (0) 8374 2409-0 | info@aip-automotive.de

www.aip-automotive.de | [in](#)

