Combining Virtual Reality and Steer-by-Wire Systems to Validate Driver Assistance Concepts

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***Abstract*— Emerging driver assistance system architectures require new methods for testing and validation. For advanced driver assistance systems (ADASs) that closely blend control with the driver, it is particularly important that tests elicit natural driving behavior. We present a flexible Human&Vehicle-in-the-Loop (Hu&ViL) platform that provides multisensory feedback to the driver during ADAS testing to address this challenge. This platform, which graphically renders scenarios to the driver through a virtual reality (VR) head-mounted display (HMD) while operating a four-wheel steer-by-wire (SBW) vehicle, enables testing in nominal dynamics, low friction, and high speed configurations. We demonstrate the feasibility of our approach by running experiments with a novel ADAS in low friction and highway settings on a limited proving ground. We further connect this work to a formal method for categorizing test bench configurations and demonstrate a possible progression of tests on different configurations of our platform.**

I. INTRODUCTION

Advanced driver assistance systems (ADASs) require rigorous testing across a comprehensive set of test cases to be safely deployed on public roads. While established tests exist for mature ADAS technology, such as automatic emergency braking (AEB) and electronic stability control (ESC), many emerging driver assistance concepts lack these prescribed validation methods. This paper addresses the question of how to test and validate novel ADASs that cooperate closely with the driver in keeping the vehicle safe and may be deployed in a wide range of operating conditions.

Standardized testing methods exist for common ADASs such as AEB and ESC. Numerous protocols have been outlined by organizations including the US Insurance Institute for Highway Safety (IIHS) [1], National Highway Traffic Safety Administration (NHTSA) [2], and the European New Car Assessment Programme (Euro NCAP) [3] for validating the safety of these systems. In contrast to established ADASs, many emerging driver assistance systems rely on continuous interaction between the driver, vehicle, and environment. Thus, new test methods are required that explicitly consider the driver's actions and sensory feedback while operating the system. As an example, one promising ADAS for lane keeping, designed by Arwashan *et al.*, ensures that the driver's steering input is always within a safe set and gradually assumes increased control authority as the vehicle approaches less safe states [4]. Model predictive control (MPC) schemes are another emerging approach to shared vehicle control, as shown by Erlien *et al.* in the case of steering control [5] and by Schwarting *et al.* through a system that aids the driver with both lateral and longitudinal control inputs [6].

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Given the extensive involvement of the driver throughout operation, it is essential to validate these types of closely blended control systems in settings where the driver reacts naturally to the situation at hand. Drivers rely on multisensory feedback – notably visual, vestibular (motion-based), and haptic cues from the pedals and steering wheel – while driving, and thus these cues are critical to reproduce during tests. Underscoring this point, Moten *et al.* discuss the importance of multisensory feedback in driving simulators used to validate various ADAS designs [7].

The emergence of cooperative driver assistance concepts that smoothly blend control between driver and driver assistance system motivates the use of test platforms based around the motion of a real vehicle. Combining a virtual driving scene with a test vehicle dates back to 2007, when Bock *et al.* introduced the Vehicle-in-the-Loop (ViL) test platform [8]. The inspiration behind the ViL concept was to enable safe, repeatable, and affordable testing of driver assistance concepts while validating their functionality with the dynamics of a moving vehicle. Other research groups have since used ViL platforms to test autonomous driving functionalities, for example fully autonomous intersection management systems [9] and AEB and lane keeping-assist system (LKAS) controllers [10].

Fig. 1. An immersive platform for testing driver assistance concepts.

The test platform presented in this paper – shown in Fig. 1 – is designed around the driver, giving them visual feedback through a virtual reality (VR) head-mounted display (HMD), vestibular feedback from real vehicle motion, and haptic steering feel provided by a force feedback motor. To distinguish this platform from a broader class of systems under the name "Vehicle-in-the-Loop", we follow the terminology used by Markus Steimle and colleagues at TU Braunschweig and refer to it as a "Human&Vehicle-in-the-Loop" (Hu&ViL) platform [11]. Although tests are normally limited by the road surface friction and space available at a given test site, four-wheel steer-by-wire (SBW) technology enables a much wider range of tests by emulating the dynamics of vehicles in different conditions, for example driving on a low friction surface [12] and at highway speeds [13]. The Hu&ViL platform can reproduce the relevant accelerations and rotations on the vehicle and render accurate haptic steering feedback across different conditions to create an immersive driving experience during ADAS experiments. Compared with driving simulators built around robotic platforms, the Hu&ViL simulator does not have the same acceleration limits seen on motion platforms due to the size of the simulator workspace. Rather, motion is limited by the dimensions of the available test track, which can be expanded with the high speed emulation approach in [13].

In this paper, we present a method for testing emerging driver assistance concepts through the use of a four-wheel SBW Hu&ViL platform. With this method, we can run tests in a wide range of conditions, including low friction and highway speed settings, within a single platform on one proving ground. Experiments with a novel nonlinear MPC-based ADAS demonstrate the feasibility of this approach and showcase the flexibility of the platform. We additionally discuss how this work fits into a framework for categorizing and selecting test bench configurations and describe a possible progression of tests with different configurations of our platform.

II. TEST BENCH CONFIGURATIONS

A. Overview

The Hu&ViL platform places a driver in X1, a student-built four-wheel SBW test vehicle, viewing a rendered driving scene through a VR HMD. Integrating VR with a moving vehicle presents several challenges that were solved while developing this platform. One challenge is ensuring comfortable head tracking with multiple sensor streams. In our application, the roll, pitch, and yaw of the virtual camera update based on sensor measurements on the HMD, following LaValle *et al.*'s sensor fusion approach [14]. Through this approach, the accelerometer, magnetometer, and gyroscope data on the HMD can be used to measure the orientation of the driver's head even while the vehicle is in motion. Simultaneously, high precision GPS data on X1 determine the virtual vehicle's position and orientation in real time. By keeping the driver at a fixed eyepoint in the virtual vehicle and updating their orientation relative to the test vehicle, the combined motion of the driver and the vehicle is smoothly rendered in the virtual driving scene. More details of the hardware and software architecture of the platform can be found in [13].

This flexible platform can immerse the driver in nominal dynamics, low friction, and high speed settings, referred to as test bench configurations in this paper. By introducing simulated elements to in-vehicle testing, users can create any driving scene that fits within the bounds of the physical proving ground or, in the case of high speed emulation, to stretch these bounds. When testing on an empty skid pad, for example, we can create realistic roads with significant variety in lane width and curvature, road infrastructure, and other traffic participants. This addresses a practical challenge in ADAS testing: considerable time is often spent setting up visual boundaries for a test – for example precisely setting cones for a double lane change – or there is not a good visual reference for the driver, making it difficult to ascertain the performance of the driver assistance system.

For generality, the following test bench configurations use an ADAS that takes as input the vehicle's current position, heading, and velocity state and the driver's current steering, throttle, and braking inputs and calculates control inputs that achieve desired system behavior. This desired behavior may be matching the driver's inputs as closely as possible while deviating as needed to stay on the road and avoid collisions with other road users.

B. Nominal Dynamics

In the nominal dynamics test bench configuration, the virtual vehicle's position and orientation update in real time to match the values measured by the GPS system on X1. Thus, the driver sees their vehicle move from a first-person perspective in VR and feels the accelerations and rotations corresponding exactly to the motion of the test vehicle. A dedicated motor attached to the steering wheel on X1 renders haptic feedback to the driver using the artificial steering feel method proposed by Balachandran and Gerdes [15]. In the nominal dynamics setting, the ADAS uses the state measured by sensors on X1 and sends its calculated commands directly to X1. As such, the driver experiences full sensory feedback, and the ADAS interacts directly with the dynamics of the test vehicle. The flow of signals is depicted in Fig. 2.

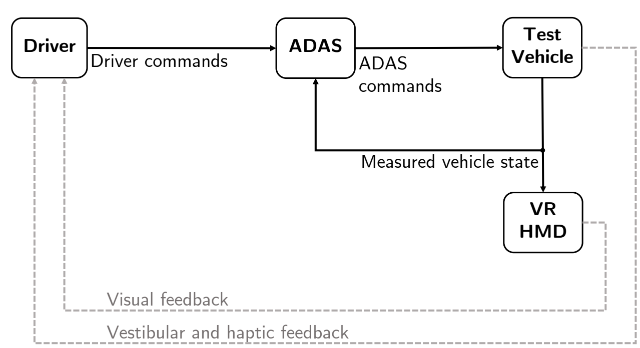

Fig. 2. The nominal dynamics ADAS test bench configuration.

C. Low Friction

The low friction test bench configuration allows the driver and ADAS to interact with a vehicle in snowy or icy conditions when the proving ground in reality has a high friction surface, for example dry pavement. The platform achieves this low friction behavior through an implementation of the low friction emulation method detailed by Russell and Gerdes in [12]. In this case, the ADAS takes as input the driver's commands and the measured vehicle state but sends its computed control inputs to a reference model. This model simulates the vehicle's yaw rate, lateral velocity, and longitudinal velocity using a double track bicycle model with a low coefficient of friction between the wheels and the road surface. The emulation controller uses a feedforward-feedback control law to calculate the front steering, rear steering, throttle, and braking commands needed to track the reference velocity states on X1. The platform additionally renders accurate haptic feedback by using the same low friction coefficient in the artificial steering feel method as in the reference model. This test bench configuration is shown diagrammatically in Fig. 3.

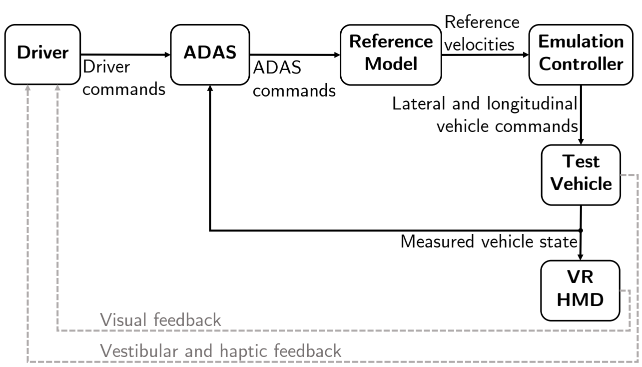

Fig. 3. The low friction ADAS test bench configuration.

Because the emulation controller tracks all three planar velocity states, the driver experiences the rotations and accelerations associated with the low friction model. Combining theses accelerations with visual feedback showing the driver navigating through a virtual snowy scene and the modified haptic feedback, the driver experiences cohesive multisensory feedback immersing them in the low friction test setting. In this configuration, it is natural to test an ADAS that assumes the same low friction dynamics, for example as a constraint on feasible trajectories in an MPC problem, as those in the reference dynamics model. We can also explore parameter or model mismatch between the dynamics assumed by the ADAS and the reference model with different friction coefficients or model fidelity (eg single track vs double track model).

D. High Speed

The high speed emulation method visually renders the ego vehicle in the virtual world traveling at a constant scalar multiple > 1 of the test vehicle speed. This approach increases the effective testing area by the speed multiplier, in practice 2-3x, enabling immersive highway speed tests to take place on a limited proving ground. The driver experiences lateral motion cues and haptic steering feedback corresponding to the higher speed motion, as described in [13].

We have modified this method slightly for use in a test bench configuration for blended control ADASs. Because the reference model computes vehicle states traveling at a multiple of the real vehicle's speed, the longitudinal dynamics in the reference model are scaled by the same factor. Thus, the reference model does not reflect the driver's true longitudinal (throttle and braking) inputs. To enable the use of a realistic vehicle model in the reference dynamics, we split ADAS testing into two phases:

1) Speed up phase: The driver maintains manual control of the reference vehicle with scaled longitudinal inputs until a target test speed is reached, exactly following the high speed emulation method.
2) ADAS activation phase: The ADAS activates as the test's target speed is reached, blending lateral and longitudinal control with the driver. The reference model simulates the same double track vehicle dynamics as in the nominal dynamics case starting at the target speed. A speed tracking controller determines the longitudinal inputs that keep the test vehicle at the reference vehicle's speed divided by the speed multiplier. The emulation controller calculates the front and rear steering commands needed to track the reference yaw rate and lateral acceleration, giving the driver accurate vestibular feedback. Fig. 4 shows this phase for ADAS testing in the high speed test bench configuration.

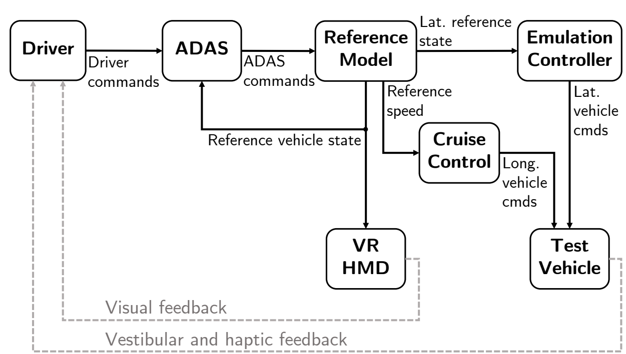

Fig. 4. The high speed ADAS test bench configuration.

With a reference model that uses realistic longitudinal and lateral dynamics during the ADAS activation phase, the ADAS can interact with a physically realizable vehicle model of arbitrary fidelity. In contrast to the nominal and low friction test bench configurations, the ADAS here uses the reference vehicle state as an input, rather than the measured state on the test vehicle. This method effectively runs a Software-in-the-Loop test of the ADAS and uses the actuators on X1 to provide multisensory feedback to the driver, creating safe and immersive tests up to highway speeds. The high speed test bench configuration offers a safe setting to test and modify ADASs for highway safety with realistic driver behavior before validating the system at full speeds.

E. Driver-in-the-Loop Configurations

Prior to testing driver assistance concepts on the Hu&ViL platform, users can prototype and develop ideas in stationary Driver-in-the-Loop (DiL) configurations. In these configurations, the driver sits at a desk, controlling the vehicle through a steering wheel and pedal set used for racing video games, and sees the same virtual world rendered in the VR HMD. The equivalent DiL configurations of the three test settings in Figs. 2, 3, and 4 are formed by replacing the "Test Vehicle" block with a module that simulates X1's four-wheel steer vehicle dynamics. The driver no longer experiences the vestibular feedback of a moving vehicle, although the simulator can render the same haptic steering feedback. The DiL configurations provide safe, low-cost testing of the full system with the same coverage of test conditions without requiring access to a full-sized vehicle or test track.

III. NMPC DRIVER ASSISTANCE

To demonstrate the capabilities of the proposed test platform, we run tests with a novel nonlinear MPC (NMPC) driver assistance system. At a high level, the system focuses on balancing two objectives that may be in tension in a blended control driver assistance setting. First, the system must keep the vehicle and its occupants safe. For the following experiments, we define safety as operating within the road boundaries, maintaining the stability and controllability of the vehicle, and avoiding collisions with other road users. Second, the system should be transparent to the driver, matching the driver's desired behavior whenever possible. Good driving behavior is rewarded by maintaining the driver's control authority, while unsafe control inputs are corrected through gradually increasing ADAS intervention.

The NMPC-based ADAS tested here extends the work of Schwarting *et al.*, integrating driver commands directly into an NMPC problem that uses a coupled lateral and longitudinal vehicle dynamics model to ensure dynamically feasibly trajectories [6]. The driver's intentions influence the NMPC problem through the objective function by computing a cost for any deviation from the driver's current commands. The optimization balances this objective with keeping the vehicle safe while respecting the dynamics of the vehicle and the road-tire friction. For the nominal and high speed test bench configurations, the friction coefficient in the NMPC dynamics matches the estimated friction of X1 on dry pavement (ie $\mu = 0.9$), while the low friction configuration naturally warrants a lower value (ie $\mu = 0.3$). Because the driver's commands are incorporated directly into the NMPC formulation, they impact the closed-loop behavior of the system in a significant way. It is critical therefore to elicit representative behavior from the driver to gain confidence that the system is working correctly.

Just as the ADAS must be aware of the driver's current control inputs, it is also important to relay information about the ADAS's intentions back to the driver. We use a technique developed by Balachandran and Gerdes to render predictive haptic steering feedback based on the difference between the driver's steering angle and the predicted steering command from the assistance system [16]. Our platform's SBW capability makes it simple to superimpose this feedback torque with the artificial steering feel torque on the hand wheel, providing the driver a clear warning when the ADAS is intervening.

IV. EXPERIMENTAL RESULTS

Two experiments illustrate the flexibility of this platform by evaluating the performance of the ADAS in different driving conditions. The goal of these tests is to determine how well the ADAS performs at keeping the driver safe while enabling them maximum control authority before intervening. In the first test, the NMPC ADAS helps a driver navigate turn 10 (a left hairpin) of the 2-mile track at Thunderhill Raceway Park in Willows, CA in the low friction test bench configuration. The other ADAS test, run on a 110 m by 200 m skid pad at Thunderhill, tasks the driver with overtaking a vehicle at highway speeds while avoiding an oncoming vehicle. A video showing these experiments is available here[1].

A. Test 1 – Cornering on Snow

The first test requires the driver to navigate a tight left turn on an emulated snowy surface with a friction coefficient $\mu = 0.3$. In the data shown in Figs. 5 and 6, the driver turns left too early, and the ADAS must provide corrective steering to keep the vehicle on the road. The vehicle then approaches the apex of the turn with too much speed, and the system intervenes once again by augmenting the driver's longitudinal commands with a braking force and helping the driver steer to the left. Throughout the maneuver, the driver's inputs are tracked until their behavior puts the vehicle in danger of driving out of the road bounds or unsafely spinning the car.

Though not shown here for brevity, the platform logs many other useful signals while testing. Acceleration and rotation measurements verify close correspondence with the equivalent states in the reference model. Haptic feedback is recorded and decomposed into artificial steering feel and predictive feedback components. These signals enable us to verify that the driver receives appropriate multisensory feedback during the test and to understand how the ADAS communicates its intent to the driver.

B. Test 2 – Highway Overtaking

A highway overtaking scenario illustrates how we can safely conduct a test that would otherwise be prohibitively dangerous in a real vehicle by using the high speed test bench configuration. In this test, the ego vehicle attempts to overtake a slower moving lead vehicle while avoiding a vehicle in the opposing lane. The VR HMD safely introduces other road users to the scenario, rendering them visually to the driver in the virtual highway scene. The ADAS relies on a prediction of the lead and oncoming vehicles'

[1] https://youtu.be/UpkZIYfzkmY

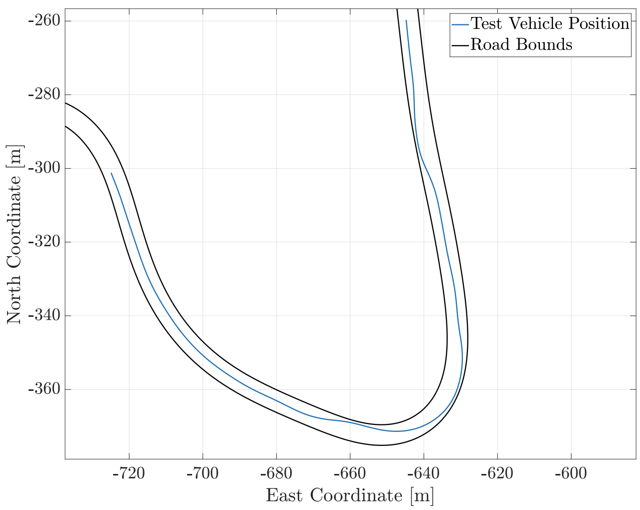

Fig. 5. Test vehicle path during low friction cornering test.

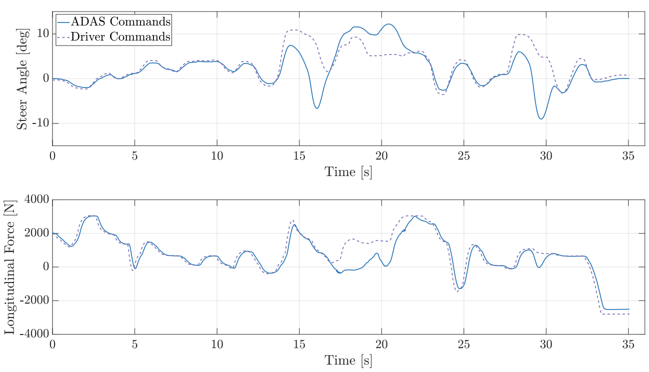

Fig. 6. ADAS and driver control inputs during low friction cornering test. Note that longitudinal force is linearly mapped to throttle and braking commands.

motion over a 3-second MPC horizon. The positions and velocities of these vehicles over the horizon are, in this case, assumed to be perfectly known by the ego vehicle. While not implemented here, the platform allows us to introduce models of environment sensors, such as cameras and radars, and uncertainty in the intent of other road users for more realistic perception.

In the results in Figs. 7 and 8, the ADAS intervenes in several ways to maintain safety. As the driver overtakes the lead vehicle, the system slightly increases the speed of the ego vehicle and helps steer to the right to keep the driver from colliding with either vehicle. After completing the overtaking maneuver, the ADAS prevents the vehicle from going off the road despite a strong steering input to the right from the driver. Additionally, the test vehicle stays within the bounds of the skid pad at Thunderhill, which only provides about 200 m of usable road length, while the high speed maneuver unfolds over more than 550 m of highway. These results illustrate the use of the high speed test bench configuration to validate the safety of an ADAS designed for highway collision avoidance.

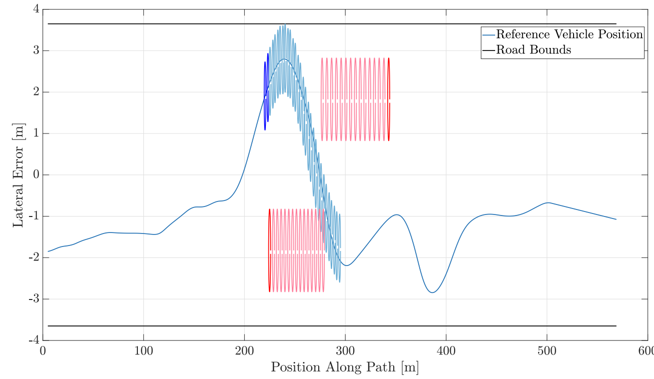

Fig. 7. Position prediction of reference vehicle (in blue) and other two vehicles (in red) over MPC horizon in path-fixed coordinates during one time step of highway overtaking test.

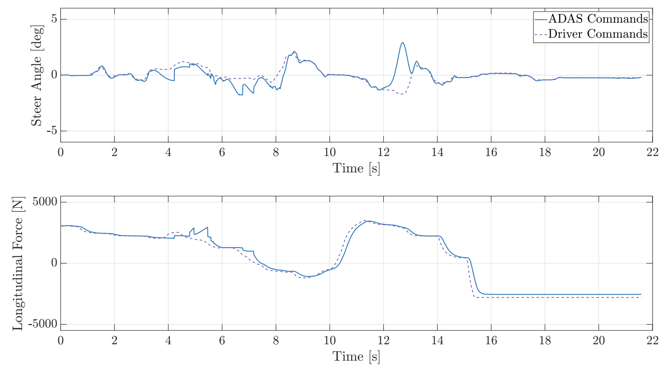

Fig. 8. ADAS and driver control inputs during highway overtaking test.

C. Human Factors

Throughout all experiments, the system provides a coherent set of visual, vestibular, and haptic feedback to the driver. Although not explicitly shown through plots in this paper, the sensory feedback experienced by drivers meets several objective metrics. For example, the yaw rate in the high speed test bench configuration falls within known perception limits [13], and the haptic steering feedback system meets various objective measures that capture qualities such as returnability and steering sensitivity [15]. The subjective experience of drivers in the proposed Hu&ViL platform reinforces the quality of sensory feedback provided across a variety of configurations and scenarios. Of note, there have been no cases of reported motion sickness across more than ten system users. Simulator sickness occurs when visual and vestibular cues are mismatched, which is always the case in a stationary driving simulator and may occur at the motion limits of a moving platform simulator. In contrast, the Hu&ViL simulator reproduces the full motion of the vehicle seen in VR – including high frequency vibrations associated with road roughness that are difficult to realistically recreate on a robotic platform – thus providing a comfortable and natural driving experience.

V. DISCUSSION

A. Framework for Categorizing Test Bench Configurations

Our experiments demonstrate an evaluation of ADAS performance in specific scenarios. Validating the safety of an ADAS requires confidence that the driver-ADAS-vehicle system will perform safely across a wide range of test cases. Schuldt *et al.* point out the exponential growth in number of tests cases with each parameter used to define scenarios and offer a method for efficient and comprehensive test case generation [17]. Even with a tractable number of test cases, further work remains to determine the best platform for testing an autonomous system in each test case. Steimle *et al.* address this challenge by categorizing test bench configurations across ten dimensions and present a method for systematically determining which test bench configuration is best for a given test case [18]. We have analyzed the three test bench configurations on our Hu&ViL platform across the same dimensions and plotted the resulting radar charts in Fig. 9.

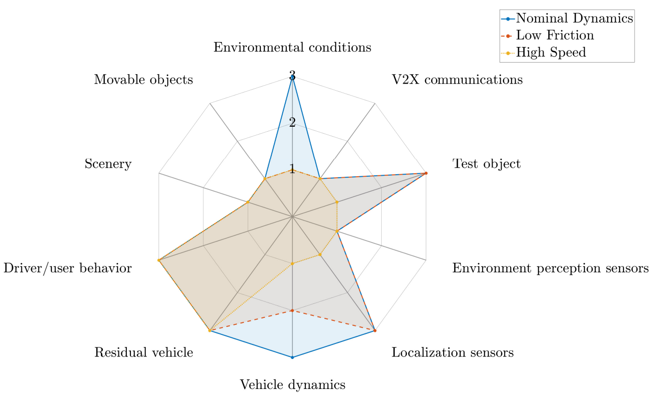

Fig. 9. Radar chart classifying the three test bench configurations. The elements are either 1 = simulated, 2 = emulated, or 3 = real.

This framework enables clear comparison between the test bench configurations possible on our platform. When validating blended control driver assistance concepts, it may be necessary to add an additional dimension for sensory feedback. This element could be split into visual, vestibular, haptic, audio, and any other relevant sub-dimensions. For example, real visual feedback would be what the driver sees in a typical test vehicle, while simulated visual feedback would be the virtual graphics in a DiL or Hu&ViL platform. On X1, the driver experiences emulated haptic steering feedback produced by an independent force feedback motor, while haptic feedback would be considered real on a vehicle with mechanical steering linkages. Through connections to the framework proposed by Steimle *et al.*, we can explore how our approach could be used to formally validate ADASs for which the driver's response to critical situations is essential to system safety.

B. Testing Progression

While developing and tuning a blended control ADAS, engineers may follow a test progression, incrementally increasing realism across various platform dimensions. Here we consider a test progression for validating an ADAS for highway overtaking on different configurations of our platform. Table I shows a possible ordering of test bench configurations and the realism attained when transitioning to each configuration, starting with DiL and Hu&ViL versions of the high speed test bench configuration.

TABLE I
EXAMPLE TEST PROGRESSION FOR HIGHWAY OVERTAKING

Test Bench Configuration	Realism Gained
High speed DiL	Driver-ADAS interaction
High speed Hu&ViL	Vestibular feedback
High speed Hu&ViL w/ sensor model	Environment sensing
Nominal Hu&ViL driven at high speed	Real ego vehicle dynamics
Test vehicle driven at high speed	Other real vehicles

Moving down the table, each test bench configuration introduces more realistic elements during testing. The third configuration listed incorporates a model of the environment perception sensors used to perceive the lead and opposing vehicles' states, rather than assuming perfect state information. Through this test, one could determine the impact of modeled sensor errors on the ADAS's collision avoidance behavior. If more testing space is available, the fourth configuration uses the nominal dynamics Hu&ViL platform at the full highway speed, enabling the ADAS to interact with the real dynamics of the test vehicle. Finally, once the ADAS is validated with other simulated vehicles, the next tests could take place alongside other real vehicles at highway speeds without VR simulation. In this configuration, real perception sensors will be used, and the driver will visually see vehicles in the real world, rather than in VR. This progression provides an example of how engineers and other practitioners could use test bench configurations of increasing realism based around a flexible platform for ADAS validation.

VI. CONCLUSION

Tests used to validate emerging driver assistance concepts that interact closely with the driver must be immersive. Placing the driver in a VR-based Hu&ViL platform on a four-wheel SBW vehicle enables a wide range of testing possibilities. In particular, we can conduct realistic low friction and high speed ADAS tests with limited proving ground access. Our experiments in these settings show the different types of data that can be collected to evaluate the performance of a given ADAS design. Analysis in the context of related work on autonomous system testing provides an understanding of how these test bench configurations may be useful in a broader validation process for emerging ADAS technology.

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