Control based driving assistant functions' test using recorded in field data

Johannes Bach*, Kai-Lukas Bauer†, Marc Holzäpfel†, Martin Hillenbrand* and Eric Sax*
*FZI Research Center for Information Technology, Karlsruhe, Germany
Email: bach@fzi.de, hillenbrand@fzi.de, sax@fzi.de
†Dr. Ing. h.c. F. Porsche AG, Weissach, Germany
Email: kai-lukas.bauer@porsche.de, marc.holzaepfel@porsche.de

***Abstract*—For verification of Advanced Driver Assistant Systems (ADAS) versatile types and levels of laboratory, as well as vehicular tests are applied. This paper presents a methodology for reutilization of recorded test data during virtual verification of control based ADAS. By changing the recorded data's domain, coherent and reactive stimulus of the System Under Test (SUT) is enabled. To do so, identification of causal dependencies between various input data streams is required. The basic feedback loop of the control system is closed by means of a conventional plant model and all additional input data is derived from conditioned data records. Therefore, introducing reproducibility to real world Rapid Control Prototyping (RCP) test, omitting time demanding scenario parametrization and ensuring realistic scenarios. Our concept is explained and demonstrated using recorded data during development of a Predictive Cruise Control (PCC) system.**

I. Introduction

Innovative ADAS for semi- and highly-automated driving challenge established methods, processes and tools for system and software development in the automotive domain. Especially during early phases of system development a gap between simulation and RCP based concepts exists, causing additional workload to keep parallel system environments synchronized. In this paper we present a novel approach to reuse recorded in field data from test runs with RCP equipped vehicles by feeding selected system inputs during Model-in-the-loop (MIL) simulation with realistic and reactive data. Since the approach is based on system interface level, demand for elaborate simulation models and adapters for different platforms are reduced to a minimum. Utilizing the approach during the preliminary development of a PCC system [1] has shown great potential regarding improved testability and lesser need for in field tests.

Product development applies a multitude of diverse methods, activities and tools, utilized by various development and test personnel in order to perform inevitable verification and validation [2]. Proving of functional content applies methods ranging from basic unit tests over static model or code analysis to highly advanced test methods such as Time Partition Testing (TPT) [3] and X-in-the-loop (XiL) simulation [4]. Particularly the latter casts an important role for test of control based systems. In addition to thorough verification, increasing functional content implies consistent and continuous validation throughout development. This is commonly achieved by equipping test vehicles with RCP control units. Exemplary systems such as MicroAutoBox or PC based tools like Automotive Data and Time-Triggered Framework (ADTF) [5] support development with a firm platform providing simplified function integration and evaluation, common communication protocols and interfaces, as well as instruments for data recording and playback. By RCP verification and validation capabilities within real system environment on dedicated compounds and public roads are provided, thereby supplying coherent and proper test cases. Nonetheless, provision and maintenance of test vehicles with prototype systems, as well as execution and evaluation of tests, is very expensive and time consuming, while incomplete reproducibility represents RCP's most enormous disadvantage.

Constantly increasing environmental perception by radar or computer vision based sensor techniques, as well as digital map data or inter vehicle communication enable semi-automated ADAS such as PCC, Lane Keep Assist (LKA) and stop and go assist. Such highly innovative technologies, used during preliminary development stage, introduce additional challenges for all facets of system development. While in the context of verification especially the demands for detailed XiL component models, flexibility in dealing with frequent refinement cycles and adequate test case definitions rise, meeting these needs is hampered by incomplete knowledge of and short experience with newly applied technologies.

Virtual testing of ADAS with unidirectional information flow, such as environmental perception or advisory elements, can be enabled and enhanced by means of replaying recorded input data [6]. In most cases however, testing control based ADAS may benefit from recorded data only to a limited extent [7], as bidirectional causality of control based systems imperatively presumes feedback of a reactive system environment, which is not provided by replaying test records.

As mentioned above, verification is typically performed using diverse methods. While unit tests allow evaluation of small subcomponents, functional testing of control based systems needs elaborated methods such as TPT, XiL and RCP. As TPT enables verification tests for system and software components, this method is very resource consuming and doesn't suit preliminary development. Reproducible testing for control based systems is supported by XiL, but designing comprehensive and coherent plant models and specifying sufficient test case variants remains an unresolved issue. In addition, validation is not possible or requires huge effort for adequate driving experience simulation. RCP systems provide real world driving experience, thereby enabling validation on public roads but hindering reproducibility. Approaches to combine RCP test data and XiL simulation, as presented in [8] and [9], exist. These approaches utilize additional LIDAR-based sensors to derive virtual driving scenarios for sophisticated simulation environments. To facilitate reactive reuse of test data gained in preliminary development of a Predictive Cruise Control System, we present a methodology to combine XiL and RCP test on system interface level. By simulating merely the system's basic feedback loop, all other necessary system inputs can be derived from conditioned data records, thereby sparing additional sensors and sophisticated environmental simulation models.

II. Proposed Methodology

Control based ADAS often rely on multiple inputs from different sources, for example camera or radar based perception systems. For virtual verification testing these need to be charged with globally coherent data streams. The aim of the proposed methodology is to provide recorded test data with reactive properties, so the records can be reused in XiL testing environments. Therefore, a causal relationship analysis of the SUT is undertaken to classify each input's dependencies. Either input may be a direct component of the system's basic feedback loop, depending on a component of the feedback loop or depending on an external source. For some signals, even combined dependencies can be identified. Such dependencies may be referred to as the signal's causal related domains.

Furthermore, the causal relations can be differentiated between being of continuous nature, for instance measured slope, and event-driven nature, for example detected traffic signs. In addition, a signal can be represented by a set of sequences, thereby being event-driven in one causal related domain and of continuous nature in another.

While all direct components of the basic feedback loop need to be simulated in the plant model to achieve a reactive XiL test bench, the other inputs shall be derived from recorded data. As these records are commonly available in time domain, which rarely depicts the sole causal related domain, they can't be used directly for reactive testing in most cases. Each remaining input either has to be mapped to its causal related domain, or disassembled into sequences with trigger events in a domain, which is part of the feedback loop. These trigger events serve as interlinks between the different domains and ensure consistency between inputs.

Let's assume a controller with three input signals $x(t), y(t)$ and $z(t)$ and output $u(t)$.

$$u\left(t\right)=f\left(x\left(t\right),y\left(t\right),z\left(t\right)\right) \tag{1}$$

Results of causal relationship analysis show that $x(t)$ is a direct component of the main feedback loop and monotonically nondecreasing, therefore suitable for unambiguous referencing. $y(t)$ is of continuous nature and depends on $x(t)$, while $z(t)$ is a sequenced signal and depends on time t, whereas its trigger event source is the feedback loop component $x(t)$. This context is represented in figure 1.

A corresponding data record with N samples and sample time Δt can be expressed as a discrete signal

$$x_n=x\left(n\Delta t\right)=x\left(t_n\right) \tag{2}$$

where n is a discrete index taking values in the nonnegative integers {0,1,2,...,N-1}, feedback loop component $x(t)$ can be

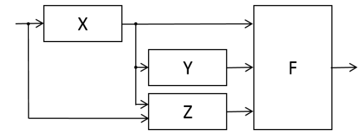


Fig. 1. Causal relationships of abstract demo control system

described as time dependent output of the utilized plant model $\hat{x}$ such that

$$\hat{x}_i=\hat{x}\left(i\Delta\hat{t}\right)=\hat{x}\left(\hat{t}_i\right) \tag{3}$$

concordantly i taking nonnegative integers {0,1,2,...,I-1}, while Δt and $\Delta\hat{t}$ scale with factor α

$$\Delta t=\alpha\Delta\hat{t} \qquad with \quad \alpha>0 \tag{4}$$

A. Continuous causal relation

For consistent reuse of the recorded signal y_r, we have to link it against the simulated input $\hat{x}_i$, its causal related domain. By substituting t_n with its causal related domain we get

$$\begin{aligned} y_n &= y\left(n\Delta t\right)=y\left(t_n\right) \\ &= y\left(x^{-1}\left(x_n\right)\right). \end{aligned} \tag{5}$$

To map x_n and $\hat{x}_i$, we need to interpolate between two non-equidistant data vectors. For this purpose we apply a function

$$g\left(a\right)=\begin{cases}1 & for\ 0\geq a\\ 0 & else\end{cases} \tag{6}$$

to the data indices. Consequently, replacement of simulation index i by record index n is achieved by

$$\begin{aligned} n &= h\left(i\right) \\ &= \sum_{j=1}^{N-1} g\left(\hat{x}_i-x_j\right). \end{aligned} \tag{7}$$

Accordingly, recorded data y can be mapped to its causal related domain by

$$\hat{y}_i=y\left(h\left(i\right)\Delta t\right) \tag{8}$$

and hence, becomes responsive to the implemented simulation model and consecutively, to the controller's output. Figure 2 illustrates resulting value $\hat{y}_i$ for two varying simulation runs. As can be seen on the left and bottom plane, mapping to $\hat{x}_i$ results in varying temporal behavior, whilst x-related behavior is identical. Furthermore, depending on scaling factor α, up- or respectively downsampling is applied to the recorded signal y_n.

B. Event-triggered signal sequences

As stated above, we assume an event-triggered sequenced signal z_n consisting of K successive signal sequences $z_k\left(t_{jk}\right)$, each of which contains J_k samples and is causally self-contained and coherent. Progression within each sequence is attributed to time t_n, its causal related domain. Interconnections between sequences are based on start times t_{0k}, which

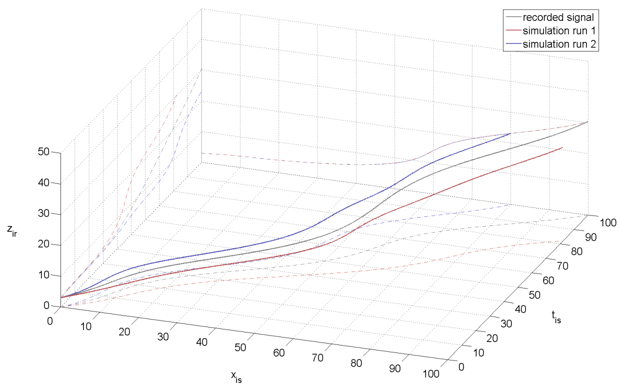


Fig. 2. Recorded data y is transformed to simulation time domain $\hat{t}_i$ by mapping x_n and $\hat{x}_i$. Variations between simulation runs result in different temporal behavior of signal $\hat{y}_i$

map to causal related domain x. Individual sequences can be expressed as

$$z_k\left(t_{jk}\right) = z\left(t_{jk} + t_{0k}\right) \cdot rect\left(\frac{t_{jk}}{J_k \Delta t}\right) \tag{9}$$

with rectangular function

$$rect\left(a\right) = \begin{cases} 1 & for\ 0 \leq a < 1 \\ 0 & else \end{cases} \tag{10}$$

limiting the scope in time domain. For the example system $z = 0$ is the undefined value. For reuse in a XiL test bench, all dependencies to record time base t_n have to be replaced by simulation time base $\hat{t}_i$. Hence, we need to replace the sequence start time t_{0k} via mapping onto $\hat{x}_i$ by

$$i_{0k} = \sum_{i=0}^{I-1} g\left(n_{0k} - i\right) \tag{11}$$

and consequently enabling replacement of t_{jk} within time dependent sequences by

$$t_{jk} = \left\lfloor \frac{i - i_{0k}}{\alpha} \right\rfloor \Delta t. \tag{12}$$

Replacing t_{jk} in equation 9 with the above and summing up all sequences, we can derive input signal $\hat{z}_i$ from recorded data by

$$\begin{aligned} \hat{z}_i = \sum_{k=1}^{K} z\left(\left\lfloor \frac{i - i_{0k}}{\alpha} \right\rfloor \Delta t_r + t_{0k}\right) \\ \cdot\, rect\left(\frac{1}{J_k}\left\lfloor \frac{i - i_{0k}}{\alpha} \right\rfloor\right) \end{aligned} \tag{13}$$

For simplification a terminus limiting the scope in x to allow only one sequence was omitted. When implementing the method, precautions are required to suppress simultaneous existence of two sequences. Sequencing signal z_n by means of causal relations, enables decoupling of recorded data from temporal dependencies. Figure 3 shows an example sequence z_k derived from recorded signal y_n. For better understanding, primarily the sequence's time base t_{jk} is used. The start of the sequence is bound to simulated value $\hat{x}_i$ by $x_{0rk} = 10$. After reaching this trigger condition, progression within the sequence is based on time t_{jk}. The gray surface depicts the scope of sequence z_k within t_{jk} and $\hat{x}_i$. As the succeeding sequence $\hat{z}_{i(k+1)}$ is not within the scope of the plot, the validity of sequence z_k ranges beyond it.

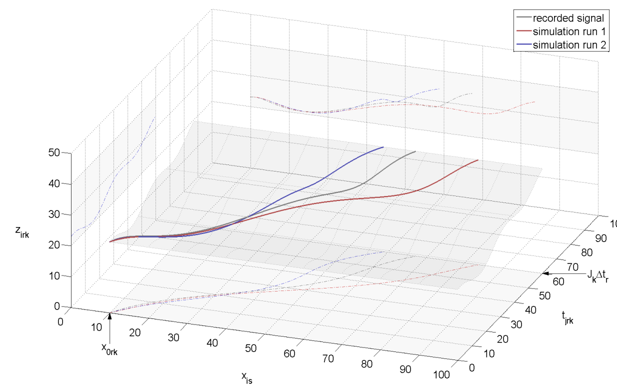


Fig. 3. Recorded Signal and example of two varying simulation runs applying event-driven signal sequence $\hat{z}_{ik}$ of length $J_k \Delta t = 60$, which is concatenated with simulated signal $\hat{x}_i$ by derived start values $x_{0rk} = 10$ and referenced to time t_{jk}

Furthermore, the recorded signal and two simulation runs utilizing the sequence with different behavior in $\hat{x}_i$ are plotted. The varying outputs of the plant model for each run can be seen in the bottom plane. On the left plane the consistency of the temporal behavior within the sequence is depicted. Concluding, on the back plane the x-related behavior is shown, which is altered between recorded signal and two differing simulation runs.

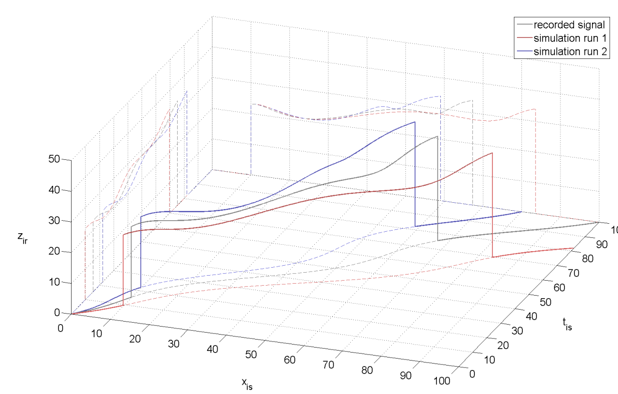


Fig. 4. Comparing full signal curves of recorded signal z_n and replayed signals $\hat{z}_i$. Scaled lateral behavior can be seen on the back plane and temporal phase shift is shown left.

Applying the simulation runs as depicted in Figure 4 to sequence z_k, yields the signal behavior shown in Figure 2. Both sequences start from differing simulation time stamps $\hat{t}_i$ as observable on the left plane. Since temporal behavior is preserved, disparity between both runs of signal $\hat{z}_i$ can be fully described by a phase shift. In reference to simulated value $\hat{x}_i$, either sequence starts approximately at $x_{0rk} = 10$, depending on curve and sampling. According to progress of $\hat{x}_i$, the scope of sequence z_k is scaled differently, thereby enabling responsive behavior to the plant model, whereas the essential characteristic of the signal is preserved and only a phase shift in time domain is applied.

In Summary, signals with a causal related domain, which is part of the simulation model, can be easily adapted to respond to the plant model. However, signals with an external domain need to be expanded with a base reference available in the simulation model, taking its causal relationship into account. Such newly referenced data samples can thus be re-fed into the control system according to their simulated reference. Hereby, reactive XiL test based on recorded data is enabled. Validation runs with RCP vehicles on common routes, can be prepared by preceding with verification against specially tailored test cases, which are derived from data recorded during previous runs on the same route.

III. Showcase System

The method described in this paper was developed and implemented for the test of a PCC System [10] in preliminary development stage. The overall aims targeted during PCC development include, in addition to reduction of driving tasks by increased automation, energy efficient movement due to advanced shift and velocity strategies. Furthermore, fundamental requirements such as safe operation and comfortable or sportive driveability apply as well.

The described system utilizes multiple sensor and data input streams of high abstraction level. This implies that all information is fed into the system via vehicle data bus from several distributed control units. The most important input sources of the system are listed below

- vehicular sensors (e.g. determination of current slope)
- powertrain controls (e.g. motor momentum)
- Adaptive Cruise Control (ACC) radar (e.g. tracked traffic objects)
- monoscopic front camera (e.g. speed limits)
- GPS localization (e.g. vehicle position)
- predictive map data (e.g. upcoming curvature)

Vehicular sensors provide signals such as the current slope of the road and atmospheric pressure. Powertrain controls deliver necessary information about vehicular speed, momentums of the engine, transmission and wheels, as well as state based data such as engaged gear number or coasting with open clutch. The vehicle's radar is integrated within the series ACC system and provides environmental perception of moving and static objects. Information about the preceding target object is of particular interest, but also further traffic objects within the vehicles surrounding are processed. The monoscopic front camera system supplies traffic sign and lane markings recognition, which are both utilized for adapting probably corrupted or out-dated predictive map data. For localization, a dedicated GPS receiver is utilized and predictive map data is supplied by a preliminary electronic horizon system.

A. *Causal relationships*

To render substitution of system inputs by recorded data possible, firstly all causal relationships of the input variables listed above need to be analyzed. Deriving those relationships is premised on identifying the components, which are part of the system's main feedback loop. The primary functionality of the system, reduced to a very fundamental specification, is the control of the vehicle's speed. Consequently, a minimum requirement to the feedback loop model is to simulate the velocity of the vehicle based on the emitted control quantities. Therefore, the vehicle's longitudinal position, in reference to the entire distance covered during the simulated test run, is deduced. Based on this primary constraint, the causal relationship analysis for all input quantities is conducted.

To obtain suitable driveability, besides controlling the vehicle's speed, a proper strategy for gear shifting is required. Generating this strategy is based on various signals such as engine, clutch and gearbox momentums and rotational speeds. Therefore, the utilized plant model implementation has to be extended to cover all powertrain components, including emulation of special preliminary functionalities provided by powertrain control systems like an interface for coasting requests.

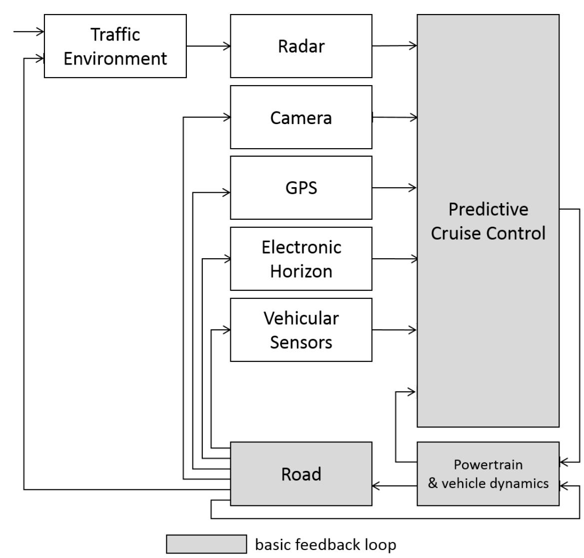


Fig. 5. Causal relationships of the predictive cruise control in system perspective

Figure 5 depicts the described powertrain model and its position within the basic feedback loop. Besides traction, longitudinal vehicular dynamics depend mainly on drag forces introduced by air and rolling resistance. To calculate a sufficiently precise drag force, an accurate road model is required within the feedback loop.

Besides the already mentioned slope estimation, the utilized vehicular input data streams comprise basic signals such as tank filling level or driver inputs. Of these, only the estimated slope has a significant influence on the controller behavior. Thereby, it's causal related domain is of continuous nature and depends directly on the vehicles position. For simplification all other inputs can be represented by static values.

The vehicle's localization is based on a common GPS receiver and predictive map data information obtained via CAN Bus from an external provider. These inputs' causal related domains are also based on the longitudinal position. Whereas GPS measurements are sampled values depending on a continuous source, electronic horizon data represents a snapshot of the upcoming track. Consecutive snapshots may be utterly different, if for example a turn is taken that wasn't represented before. Therefore, the electronic horizon's causal related domain is specified as event-driven and based on longitudinal position. Figure 6 depicts a snapshot of the system's environmental perception including GPS measurement and the electronic horizon.

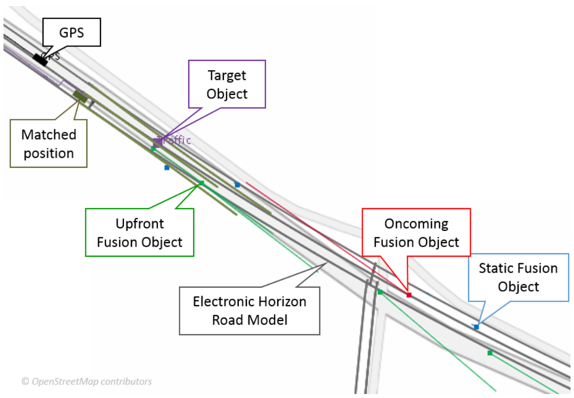


Fig. 6. Example scene demonstrating the environmental perception of the PCC system including radar target and fusion objects, electronic horizon, GPS measurement and matched position. The background shows a globally valid reference map.

Incoming data from the vehicles monoscopic camera system comprises detected traffic signs and road markings. Thereby, detected traffic signs can be characterized as a spontaneous event-driven data stream, whereas detected road markings are of continuous nature. If there are no road markings available or cannot be determined, the signal assumes an invalid value. Based upon this characterization, the causal related domain of the camera data stream is split up into an event-driven and a continuous part. Furthermore, the detected road markings are utilized to adjust imprecise curvature information within the system. In summary, both signals' causal related domains are the longitudinal position on the test track with either event-driven or continuous nature.

Environmental perception of traffic objects is based on the series ACC radar system. Generally, the integrated radar provides two different kinds of recognized objects, one target object and a fixed number of so called fusion objects. The former is derived from the recognized fusion objects and identified as the next upfront road user within the same lane. Based on the target object, the series ACC system controls the vehicles speed. Fusion objects differ between upfront, oncoming and static objects and may be classified into vehicle types depending on signal quality. Whereas the target object is indicated by one-dimensional values for relative distance, velocity and acceleration, fusion objects are referenced by two-dimensional xy-vectors for position, velocity and acceleration relative to the ego vehicle body frame. Hence, these input signals depend for one hand on the objects movement and are on the other hand linked to the movement of the ego vehicle as well. This causal relation is shown in figure 5. The traffic objects' respective behavior and trajectory originally depend on the object's surroundings and its controlling instance, which most frequently still is a human driver. We assume the influence of the PCC to the driver of a upfront vehicle is not significant. For the sake of convenience and the lack of sensible alternatives, the causal related domain of objects' movement is specified by time. To enable reactive properties, decoupling of the temporal behavior from the ego vehicles movement is necessary, while at the same time existence of each object still needs to be linked to the ego vehicle. Accordingly, for each target and fusion object, a temporal sequence as described above has to be derived. To keep the test cases consistent, each sequence is linked to the ego vehicle by the ego vehicle's position at first object's occurrence. Thus, passage of this position by the ego vehicle during simulation serves as start event of the respective sequence. Further, the reference of the objects' movement and position to the ego vehicle body frame needs to be exchanged by a globally valid frame, both in the one and the two-dimensional case.

B. *Mapping signal domains*

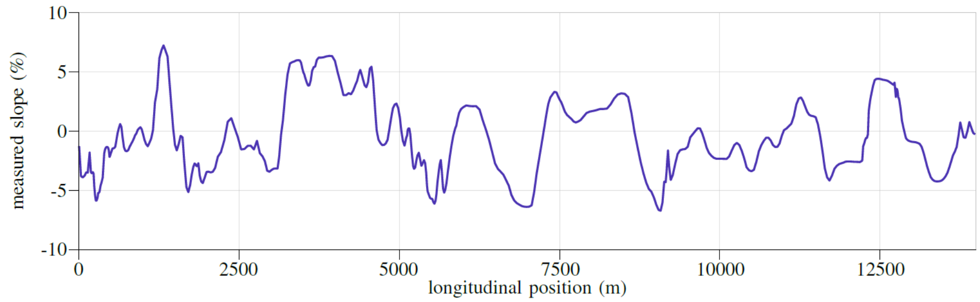
During causal relationship analysis, we specified two principal reference domains. All processes the input signals are based on can be reduced to these domains. To achieve uniqueness when mapping the recorded signals to their causal related domain, a necessary assumption to the utilized reference is monotone nondecreasing. This naturally applies to simulation time and can be ensured for the one-dimensional track position by defining it as integrated absolute velocity over time within the simulation model.

An example of a positional dependent signal of continuous nature is the measured slope of the track. Figure 7(a) depicts the measured slope signal of a recorded test run mapped to longitudinal position. For comparison, velocity sequences of recorded target objects, which display a time dependent signal of event-driven nature if concatenated, are pictured in Figure 7(b). During the depicted test run three longer and several short occurrences of target objects arose.

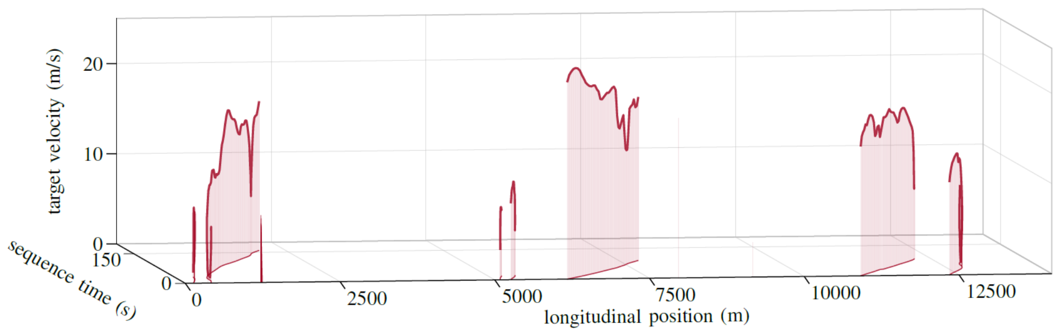
IV. Implemented Model in the Loop Test Bench

The terminologies for different XiL approaches can be ambiguous. According to [11] a major distinction between MIL and Software-in-the-loop (SIL) approaches are hardware related resource restrictions. For preliminary development of the PCC system a x86-64 based RCP system running an ADTF instance is used. Therefore, the term MIL test bench is used in this paper.

For conditioning of recorded test data, all streams are grouped corresponding to their causal related domain and nature. For each sample, all signals of continuous nature and positional domain are grouped within one data frame and saved in ascending order. Therefore, coherence between different inputs is ensured. In the following, all recorded electronic horizon data is processed. For that matter, all coherent data samples belonging to one snapshot of the upcoming track are merged into one data frame for subsequent reuse.



(a) Slope measured during a test run on a public road mapped to longitudinal position



(b) Extracted sequences of target objects recorded during a test run with the prototype system on a public road

Fig. 7. Showcase view of comparison between position based slope measurement and time based, but positional triggered, sequences of ACC target objects derived from recorded test data

Both target and fusion objects take up a more complicated part in preprocessing the recorded test data for reuse within the MIL test bench. Whereas the target object is a single input stream, the different fusion objects are described by a fixed array of parallel streams. In the first step, these parallel signal streams are searched for included object sequences. Thereby, a sequence is specified by the interval between the object's first appearance and its disappearance. Each sequence is registered in a list with its trigger position, type and in case of a fusion object, with the respective array index.

Subsequently, for each sequence the successive time-frames are extracted from the continuous data stream. Along with extraction, the relative position, movement and acceleration quantities of the objects are replaced. Velocity and acceleration of the target object are transformed to absolute values and relative distance is translated to a globally valid position on the track. The two-dimensional position of fusion objects is transformed to geocoordinates in WGS84, which is the geodetic system utilized by the GPS receiver and the electronic horizon. Velocity and acceleration are transformed to a scalar value and direction pair with reference to the earth model.

In the following, the conditioned record data can be utilized in a MIL test bench to charge the system inputs. The test bench consists of three main modules, the powertrain simulation, the electronic horizon provider and the replay management module, as well as supplementary components for scheduling, test management and evaluation. Based on the longitudinal track position, calculated within the powertrain simulation module, the preconditioned data frames are picked from the conditioned data record file by the replay manager module and injected into the SUT. The electronic horizon packages

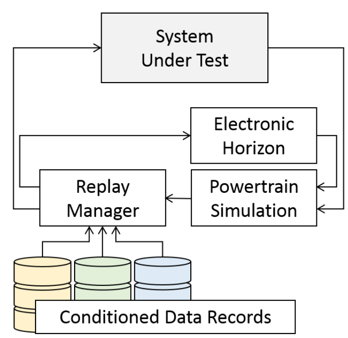
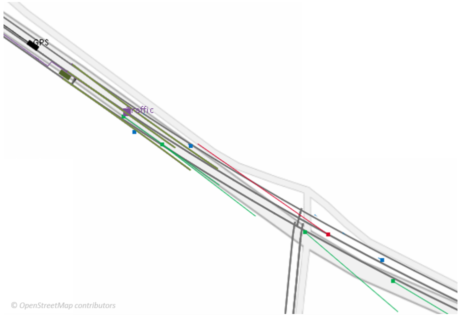


Fig. 8. Schematic of the utilized SUT test bench with powertrain simulation, electronic horizon provider and replay manager, omitting supplementary modules for scheduling, test management and evaluation

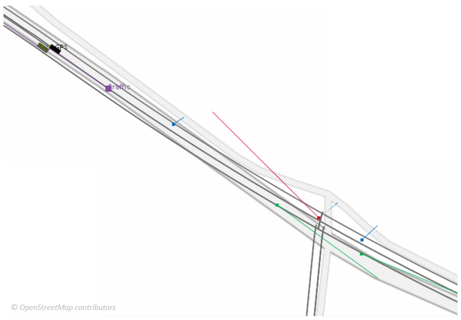
available in the conditioned data record are, in addition, fed into a separate electronic horizon composer to provide the powertrain simulation with a detailed road model. Figure 8 outlines the data and information flow within the test bench.

The test bench connects to an input bus of the SUT, which is composed of all signals selected from the various vehicular bus interfaces of the RCP vehicle. Therefore, no recomposition of CAN messages or complex CAN bus simulation is needed.

Each data frame of the conditioned data records is sampled and injected without any adaption to original sampling rate or interpolation between adjacent frames. Although signals adopt a volatile, non-equidistant curve by doing so, the effect can be neglected as the test bench's simulation frequency is sufficiently faster than the dynamic range of the input signals.



(a) Snapshot view of orignial recorded perception data



(b) Snapshot view of conditioned perception data reused in the MIL test bench

Fig. 9. Comparison of environmental perception between recorded data and re-fed data during MIL test at a similar track position

Reconstructing the two-dimensional velocity and acceleration of fusion objects relative to the vehicle is particularly challenging. Mapping from relative base frame to global base frame requires information about the position and orientation of the ego vehicle. This information is estimated from the combination of GPS course over ground, electronic horizon and lane recognition within the SUT and utilized for preprocessing the recorded data. During MIL test run, position and orientation are determined only by the road model. Therefore, particularly for small values of acceleration and velocity the presented approach introduces deviations. Figure 9 compares to snapshots of visualized environmental perception, with figure 9(a) illustrating original perception within recorded data and figure 9(b) illustrating the derived environmental perception during simulation.

V. Conclusion and Future Work

This paper presents a methodology for reutilization of recorded test data during virtual verification of control based ADAS. By changing the recorded data's domain, coherent and reactive stimulus of the SUT is enabled. To do so, identification of causal dependencies between various input data streams is required. The basic feedback loop of the control system is closed by means of a conventional plant model and all additional input data is derived from conditioned data records. Therefore, introducing reproducibility to real world RCP test, omitting time demanding scenario parametrization and ensuring realistic scenarios.

This approach was and is frequently utilized and improved during development of a PCC system. Already a broad base of recorded test runs with associated traffic scenarios exists. The approach is particularly suited for repetitive tests enabling parameter variation and exploration, and, to a certain extend, introduces virtual validation capabilities.

Future research aspects include identification of further use cases and limitations of the approach and the extension of two-dimensional time and position domain to a three-dimensional domain of time, longitudinal and lateral position, thereby enabling tests for lateral control systems. Further useful improvements include, beside others, the integration of automated evaluation methods and reports, thereby enabling utilization of the approach in combination with regressive testing and continuous integration strategies.

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