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# 硬件在环测试台模拟车辆电池的电压分布

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**摘要：** 驾驶辅助系统不仅是为了辅助驾驶员进行一般的驾驶活动，而且要能在关键情况下接管驾驶。使用原型车进行试驾是测试该系统最现实的方式，试驾可使驾驶辅助系统暴露在各种实际环境下，从而检查其可靠性。由于带有原型的测试驱动器成本很高，而且难以完全相同方式复制驾驶活动，因此在系统开发和测试过程中经常使用硬件在环(HiL)测试台。HiL 测试台不仅提供相关硬件，还可以为这些被测系统(SUT)提供模拟环境。在实际车辆的试驾过程中，由于不同的环境影响，电气系统的电压会发生变化，这些变化是基于不断变化的电气负载影响。目前，车辆电气系统的电压变化无法在硬件在环测试台上模拟。为了确定电压变化的原因和潜在现象，需要对实际试驾记录数据进行检查，以了解潜在现象。然后将这些结果用于推导唯象激励，该唯象激励可用于模拟测试台上的真实电压曲线。本文分析了车辆测量结果，目的是找出车载电压长期和短期热变化的可能原因，提出一种在 HiL 测试台上进行虚拟测试驱动的情况下真实模拟电压变化的方法。

**关键词：** 汽车测试；硬件在环；模拟测试；电池电压；驾驶试验

**中图分类号：** U467 **文献标志码：** A

## Simulation of Realistic Vehicle Battery Voltage Profiles on Hardware-in-the-Loop Test Benches

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**Abstract：** Driver assistance systems are designed not only to support the drivers in their general driving activities but also to be able to take over in critical situations，too. Test drives with a prototype vehicle are the most realistic way to test these systems. The test drive exposes the systems to all kinds of environmental influences and examines their reliability. Since test drives with prototypes are very costly and difficult to reproduce in the exact same way，hardware-in-the-loop (HiL) test benches are often used in the development and testing process. HiL test benches providing the relevant hardware and can also provide simulated environmental influences for these systems under test (SUT). During test drives with real vehicles，variations in the electrical system voltage occur due to the different environmental influences. These variations are based on changing electrical loads. Currently these variations in the vehicle electrical system voltage cannot be simulated on HiL test benches. In order to identify causes and underlying phenomena of the variations，recorded data from real test drives are examined with respect to possible phenomena. These results are then used to derive a phenomenological stimulation that can be used to simulate realistic voltage curves on test benches. The paper analysis vehicle measurements with the aim of finding possible causes for the long and short-therm change of the on-board voltage. This paper presents an approach for realistic stimulation of voltage variations in the context of virtual test drives on HiL test benches.

**Key words：** automotive testing；hardware-in-the-loop (HiL)；shift test effort to simulation；battery voltage；test drive

## 1 Motivation and introduction

In recent years，there has been an increased focus in automotive development on driver assistance systems. These systems are designed to support the driver in his driving tasks. The term "partially

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automated driving" is used when the vehicle steers itself on partial routes without input from the driver. The functions of partially automated driving must be highly reliable, otherwise there will be no acceptance of the systems by users[4-5]. Extensive testing is therefore necessary. The most realistic way of testing is to test drive a prototype in which the systems are installed. The test drive exposes the systems to all environmental influences and allows their reliability to be examined. Test drives are timeconsuming and expensive[5]. In addition, test drives cannot be repeated with the same conditions. Too many influences change: traffic is never the same, weather fluctuates, and the vehicle ages. To perform cost-effective and repeatable tests, hardware-in-the-loop (HiL) test benches are used. On such, the systems under test are built in hardware and are exposed to simulated environmental conditions. An exemplary setup of the simulation can be a monitor on which driving sequences are played back. The camera of the system can use this image as input and evaluate it. The image on the monitor can now be modified to simulate scenarios as they occur in reality. On the one hand, this concerns the objects to be recognized, i. e. pedestrians, cyclists, street signs, roads, etc., but also environmental influences such as fog or rain[4,6-7].

The supply voltage is an important environmental influence on electronic systems (ECU). In the vehicle, this was provided by the power supply battery. This environmental influence is to be mapped on the test bench. Traditional approaches to the simulation of on-board power supply voltages deal with physical models of suppliers and consumers[8-9].

This requires comprehensive measurements and analyses of the vehicle electrical system. These have to be repeated when parts of the on-board power network change. Such a comprehensive simulation is only useful in the context of energy management. Energy management deals with the power balance and electrical loads in the vehicle. By selectively switching consumers on and off, the battery's state of charge (SoC) of the battery is kept at a level that can be used to ensure future startups. The need for this is reflected in the ADAC breakdown statistics, in which vehicle batteries cause the majority of failures[3]. For this purpose, an attempt is already being made in advance to create a model for the battery with a focus on component testing by modelling a battery in detail according to Buccolini[10] and Yan[11].

In this paper, a new approach to simulate realistic on-board voltages is developed. This approach does not require any prior knowledge of the system and was developed entirely from measurements taken from a test vehicle. The measurements include information on the vehicle voltage, vehicle current, vehicle speed, braking torque and other relevant bus signals. The stimulation is not required to be highly accurate It should behave as realistically as possible. The simulated voltage does not have to correspond exactly to the measured voltage, but must exhibit the same behavior. The aim is to be able to replace the actually constant voltage on the HiL test bench at Mercedes Benz with a realistic dynamic voltage. This enables realistic testing and allows stimulation for stress and endurance running.

## 2 Requirements for state of charge model to stimulate voltage on HiL test bench

As described in Section 1, the vehicle electrical supply voltage is not constant while driving. At the start of the journey, the battery supplies the vehicle, causing the voltage to drop to the discharge voltage of the battery. This depends on the discharge current, i. e. the active electrical loads. While driving, the battery is charged, raising the whole on-board voltage. At the end of charging, the vehicle electrical system voltage is regulated to a voltage at which the charge is maintained. The power requirement in the vehicle electrical system changes constantly as electrical consumers are switched on and off. If the power consumption of the consumer is high and the switching is fast, the controller of the generator does not manage to compensate for the load change. This results in short-term overvoltages and undervoltages.

The form of these depends on the energy management strategy of the vehicle, the topology, the state of charge of the battery and the engine speed[12].

The aim of this work is to develop a model that reproduces these changes in the vehicle electrical system voltage. The simulation is to be performed in real time on a HiL test bench[13]. The model is based on measurements from a test vehicle. It is important that the simulated on-board voltage behaves realistically in the end. This means that the on-board voltage in the vehicle is subject to physical limits, which must be observed in the simulation (see Fig. 1).

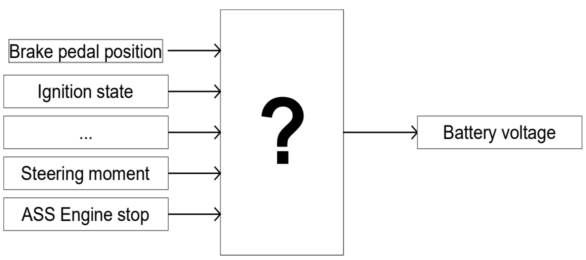


**Fig.1 Problem definition**

Since the task of the HiL test bench is to test driver assistance systems while driving, the simulation should be designed for this purpose. Thus, it is not intended to test specific scenarios, such as EM compatibility tests according to ISO 7637-2, but to simulate the voltage curve that actually occurs during a test drive[6]. This excludes, for example, a negative voltage caused by reverse polarity jump-starting. Accordingly, the selected solution approach should offer possibilities for extensions and improvements. A modular approach is selected.

The following requirements for the stimulation model can be derived based on the environmental conditions:

Req. 1 Adaptivity for new measurements: It must be possible to quickly integrate new measurements into the model.

Req. 2 Realistic behavior: The on-board voltage has physical limits that must be taken into account by the model.

Req. 3 Modularity: Individual parts of the model should be interchangeable to allow improvements.

# 3 Concept and solution strategy

Based on the environmental requirements, a stimulation model is developed for a HiL test bench.

## 3.1 Analysis of vehicle measurements

Real vehicle measurements represent the basis of the stimulation model. The measurements contain recorded voltage and current characteristics including further bus messages on the various vehicle buses. Based on these signals, which can also be accessed on the HiL test bench, the voltage stimulation model must be created. The signals of the measurement are divided into the following categories:

Power data: current and voltage signals.

Operating states: signals reflecting a certain status of a system (like vehicle speed).

External factors: environmental influences detected by the vehicle (like object in blindspot of vehicle).

Driving influences: Influences caused by steering and controlling the vehicle (like brake pedal position).

Over 50 hours of vehicle measurements were studied as part of this paper.

## 3.2 On-board power supply—topologies

The structure of a single-battery electrical system is shown in Fig. 2. The left side of Fig. 2 shows the generator and the battery. On the right side the combined consumers are shown. The generator charges the battery and supplies power to the electronic systems while the vehicle is in motion. The battery provides support during peak loads while driving and takes over the supply during engine standstill and, depending on the design of the vehicle, also during low engine speeds, such as idling.

Initially, the alternators were still DC generators with the same nominal voltage as the battery. With the introduction of the three-phase alternator in the motor vehicle, the operating voltage also became variable. Instead of 12 V, a higher operating voltage, 14 V, could be used. On the one hand, the 14 V accelerates the charging of the accumulator, and on the other hand it reduces wiring losses. With a higher on-board voltage, a lower current is required for the same power. According to $P_L = R_L I^2$, a lower current also leads to less wire losses $P_L$ due to the wire resistance $R_L$. This was also a motivation when trying to introduce 42 V on-board networks.

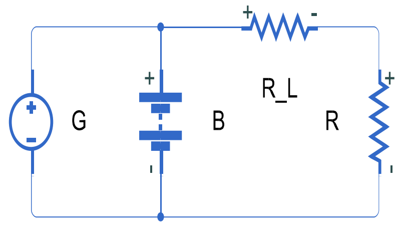


**Fig.2　Single-battery on-board power supply**

### 3.3　Electrical consumers in the vehicle

The most important long-term consumers are listed in Tab. 1. Their consumption is based on conditions that do not change during the drive. The use of car radios and navigation systems only changes over a long period of time. Together with the continuous consumers, the long-term consumers represent the base load while driving. The consumption of these systems cannot be reduced without limiting either road safety or the user experience[14]. Since the base load remains stable over the driving time, it has little effect on the on-board voltage. The generator and battery are designed on the basis of the expected base load.

**Tab.1　Electric long term consumer based on Ref [8]**

| Name | $P_{\varnothing}$ | Domain |
|---|---|---|
| Boundary lights | 4 - 5 W | Body & Cabin |
| License plate light | 10 W | Body & Cabin |
| Parking light | 3 - 5 W | Body & Cabin |
| Headlight | 55 W | Body & Cabin |
| Taillights | 5 W | Body & Cabin |
| Electric radiator fan | 200 - 800 W | Body & Cabin |
| Wiper | 80 - 150 W | Body & Cabin |
| Instrument lights | 2 W | Infotainment |
| Car radio | 15 - 30 W | Infotainment |
| Navigation system | 15 W | Infotainment |

The electric short-term consumers are only required depending on specific driving situations. They are active for short periods. Due to the high energy requirements of individual consumers, electric short-term consumers need special attention in order to keep their influence on the vehicle electrical system voltage low[3]. This can be done by selectively switching off short-term consumers with low priority or installing doublelayer capacitors[15]. If higher power is required by the electric consumers than available to the power system, the battery is discharged while driving and the on-board voltage drops to the discharge voltage of the battery[16].

### 3.4　Identification of operating states

Fig. 3 shows the battery voltage and the battery current versus time during a test drive. The auxiliary lines for the voltage curve are at 13 V and can be used to detect the state of charge, as shown by the associated current curve. At the beginning of the drive, the battery is charged and a voltage determined by the charging algorithm is generated by the generator. During this process, the voltage increases linearly while the current decreases linearly. Half an hour after the start of the trip, the battery current is negative, the battery is discharged, and the voltage drops below 13 V. In the following two hours, the voltage takes an average value of 13 V. During this period, the battery current is only slightly positive, the battery charge is held.

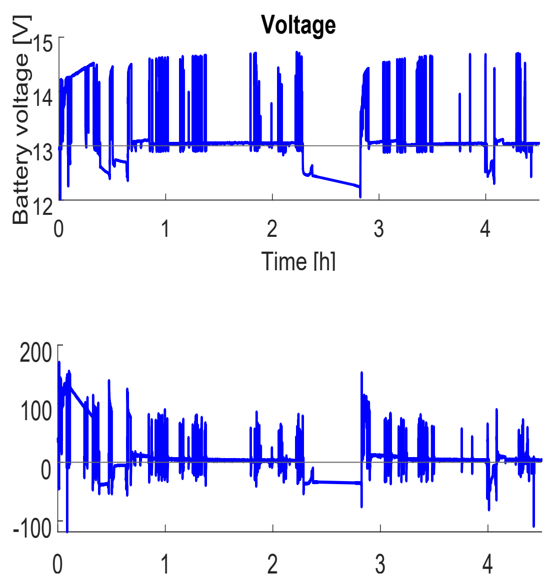


**Fig.3　Voltage and current during a test drive**

Based on the electrical consumers and the topology of the board network the real voltage curves can be analyzed and interpreted. The states of charge listed in Tab. 3 can be reproduced based on the measurements. These long-term power states are overlaid by short-term overvoltages and undervoltages, which can occur due to the switching

**Tab.2 Electric short term consumers based on Refs. [3,8-9]**

| Name | $P_{\varnothing}$ | Domain |
|---|---|---|
| Indicator/brake lights | 21 W | Body & Cabin |
| Interior light | 5 - 10 W | Body & Cabin |
| Electric window opener | 150 W | Body & Cabin |
| Electric sliding roof | 150 - 200 W | Body & Cabin |
| Rear window heating | 120 W | Body & Cabin |
| Rear window wiper | 30 - 65 W | Body & Cabin |
| Fog light | 35 - 55 W | Body & Cabin |
| Reversing light | 21 W | Body & Cabin |
| Windows and headlight cleaning | 50 - 100 W | Body & Cabin |
| Electric seat adjustment | 100 - 150 W | Body & Cabin |
| Electric mirror adjustment | 20 W | Body & Cabin |
| Heated seats (per seat) | 100 - 200 W | Body & Cabin |
| Steering wheel heater | 50 W | Body & Cabin |
| Electric auxiliary heating | 300 - 1 000 W | Body & Cabin |
| Motor antenna | 60 W | Infotainment |
| Cigarette lighter | 100 W | Infotainment |
| ESP | 600 W | Vehicle motion & Safety |
| Electric power steering | 1000 W | Vehicle motion & Safety |
| Force feedback steering wheel | 600 W | Vehicle motion & Safety |
| Active damping | 3 000 W | Vehicle motion & Safety |
| Active roll stabilization | 2 500 W | Vehicle motion & Safety |
| Electromagnetic valve control | 3 400 W | Vehicle motion & Safety |
| Electromechanical brake | 2 000 W | Vehicle motion & Safety |
| Brake by wire | 2 000 W | Vehicle motion & Safety |
| Starter | 800 - 3000 W | Powertrain |

on and off of loads or, for example, due to braking actions. The defined state of charge must be predicted by the developed method.

**Tab.3 Long-term state of charge during the test drive**

| Power balance on-board network | State of charge battery | Onboard network voltage/V |
|---|---|---|
| $P_{load} > P_{gen}$ | Discharge | Discharge voltage < 13 |
| $P_{load} < P_{gen}$ | Charge | Charge voltage > 14 |
| $P_{load} \approx P_{gen}$ | Hold | Hold voltage ≈ 13 |

### 3.5 Possible solution for state of charge prediction

In the previous sections, the problem definition and the information given for the solution were presented. Fig. 1 summarizes the problem graphically. A model is needed that can output an on-board power supply voltage based on the given signals.

(1) Model based simulation: Simulations of the on-board power supply in the literature deal with models from the point of view of energy management[17,15,3]. The aim of energy management is to prevent voltage drops while driving. In addition, good energy management ensures that the battery is kept in a state of charge that guarantees future starts. To this end, consumers can be actively switched off or the idle speed can be raised while driving. In these models, the generator and battery are mapped using a physical model. For this purpose, their characteristics are determined with the aid of measurements. Load scenarios are then specified in the simulation and the voltage curve is evaluated under various aspects. The aim of such tests is to evaluate and improve energy management strategies[3].

The guarantee of realistic behavior is one advantage of this approach. Furthermore, it is possible to perform a simulation according to this approach in real time. Since the suppliers and consumers are simulated individually, the approach is modular. The integration of new measurements is costly. The implementation of this model is extensive and time consuming. In addition, information about the individual components is needed. Since the generator and battery must be parameterized and the speed of the engine must be known for the simulation of the generator, this approach could not be chosen[18].

(2) Simulation through end-to-end AI: The next approach considered is an end to end learned neural network. In such an artificial intelligence (AI), the entire black box from Fig. 1 is replaced with a deep neural network. The output voltage is learned directly from the signals in the measurement.

The method could be adapted to new measurements, because the network only needs to be relearned. In addition, model building can take place without prior knowledge completely. Real-time execution can be assumed, since such networks are used in the image processing for driver assistance systems. The implementation is very extensive without libraries, since the complete network would have to be coded. In addition, the approach is not modular. In conclusion, completely learned systems can exhibit anomalous behavior, through which realistic behavior cannot be guaranteed. The range of values for the output voltages is not limited. As a result, high voltages could be applied and the control units in the test bench could be destroyed.

(3) Mixed simulation: Both approaches presented so far have clear advantages and disadvantages. Simulation by a model of consumers and utilities requires a lot of information that is not given, but can guarantee realistic behavior. On the other hand, an end-to-end learned network provides a way to simulate completely without system knowledge, but may behave unrealistically. To combine the advantages from both approaches, a mixed approach was chosen. For this, the state of charge is to be detected by machine learning, but the voltage itself is to be generated by a model from the power data. The model guarantees a realistic behavior, while the machine learning enables a simulation with little prior knowledge. This approach could be used completely modular. The detection of the state of charge can be changed or extended independently of the model behind it. This also allows new measurements to be quickly adapted for simulation. The above mentioned solutions are real-time executable, this can be assumed for the combined approach, too.

(4) Selection of the solution approach: As can be seen from the previous sections, the mixed approach was chosen. This was confirmed with the help of a utility analysis. The different solutions were evaluated using the requirements in Section 2.

In general, the concept consists of two parts. In the first part, the signals from the measurement have to be read in and the corresponding relevant features and signals have to be selected and extracted. The stimulation model must be trained on the basis of the existing measurements. Afterwards, this trained model can be transferred to the HiL test automation tool in the second part. In principle, the goal of the model is to determine the state of charge (see Fig. 4).

To perform the classification, relevant signals (features) must be selected. The selection of the features influences the accuracies of the classifications in the blocks "Recognition charge/discharge" and "Recognition over/under voltage" directly. With charging and discharging, the state of charge of the on-board power supply is detected. The state of charge changes only in the long-term perspective. With the help of the battery model, in which the discharging behavior and the charging algorithm are introduced, the average on-board power system voltage is generated. The battery model is based on Ref. [19], with separated charging and discharging behaviours. As explained in the signal analysis in Section 3.4, there are short-term changes in the average on-board voltage, too. These are called overvoltages and undervoltages. A model is created for these in order to be able to simulate them realistically. Finally, the outputs of the models are combined.

## 4 Implementation and evaluation

This concept was implemented as an example on a driving assistance HiL test bench. For this purpose, a digital test drive was set up according to Wohlfahrt[4]. A vehicle was simulated in a real highway environment. In this setup, the voltage stimulation model has access to all required and relevant bus messages (e. g. vehicle speed or braking torque) and runs in parallel to the digital test drive in a real-time thread[4]. The main challenge in the implementation was to make the machine learning network real-time capable. In the case of this work, ProvetechTA was used as the test automation tool.

As already mentioned in Section 3.4, the SoC model was trained before the model could be executed on the test bench. For this purpose, the recorded real vehicle measurements were read in and further processed with the help of the mixed approach presented in Section 3.5 (4). In principle, a distinction was made between the short-term and long-term voltage curve. By resimulation of the voltage curve, the results shown in Fig. 5 were obtained for the simulated voltage. A well correlated voltage curve, with the same power states and similar short term changes, can be seen. For evaluation, the trained classifier was compared to an original measurement.

Fig. 5 shows the measured voltage in the vehicle compared to the simulated voltage determined by the trained classifier. In the next step, the classifier was translated into real-time code and executed on the HiL test bench as part of a digital test drive.

Fig. 6 shows the results of the vehicle electrical system simulation during a virtual test drive on the test bench at Mercedes Benz. The X-axis shows the elapsed time in seconds after the start of measurement. The results were designed using the battery stimulation model constructed according to Fig. 4. Both long-term and short-term voltage curves were simulated. The measurement on top of Fig. 6 shows the output voltage of the power supply. The system is charging the battery at the beginning. The voltage increases over time towards 14.5 V. Once 95% charge is reached for the battery, the voltage drops to 13.05 V and the charge is held. During the holding, several peaks are detected. Between 1 800 and 2 000 seconds, two drops in voltage are seen. Beside the voltage signal, three other signals are shown: The current vehicle speed in km/h, the status of the brake pedal and the current braking torque of the service brake (from top to bottom). The simulated voltage peaks correlate with the braking torque. The simulated voltage thus behaves like the voltage from the measurements. Short-term drops correspond to the simulation of high-power consumers, through which the consumer power briefly exceeds the generator power.

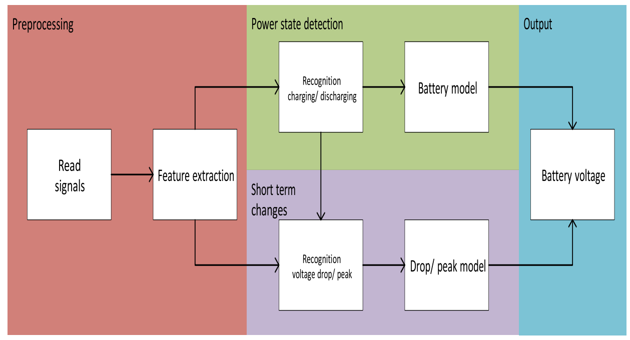


**Fig.4 Detailed solution approach**

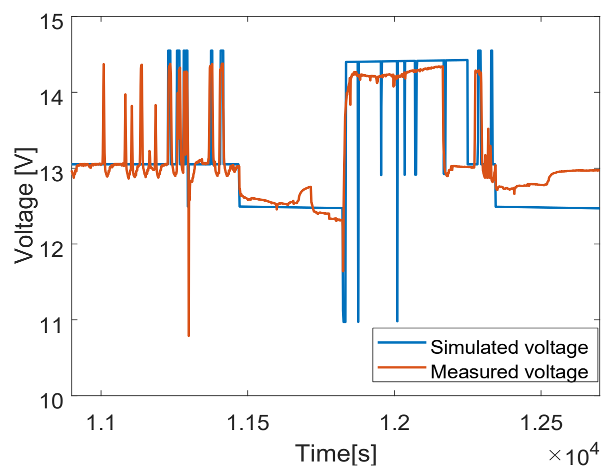


**Fig.5 Simulation of the vehicle electrical system voltage based on a vehicle measurement**

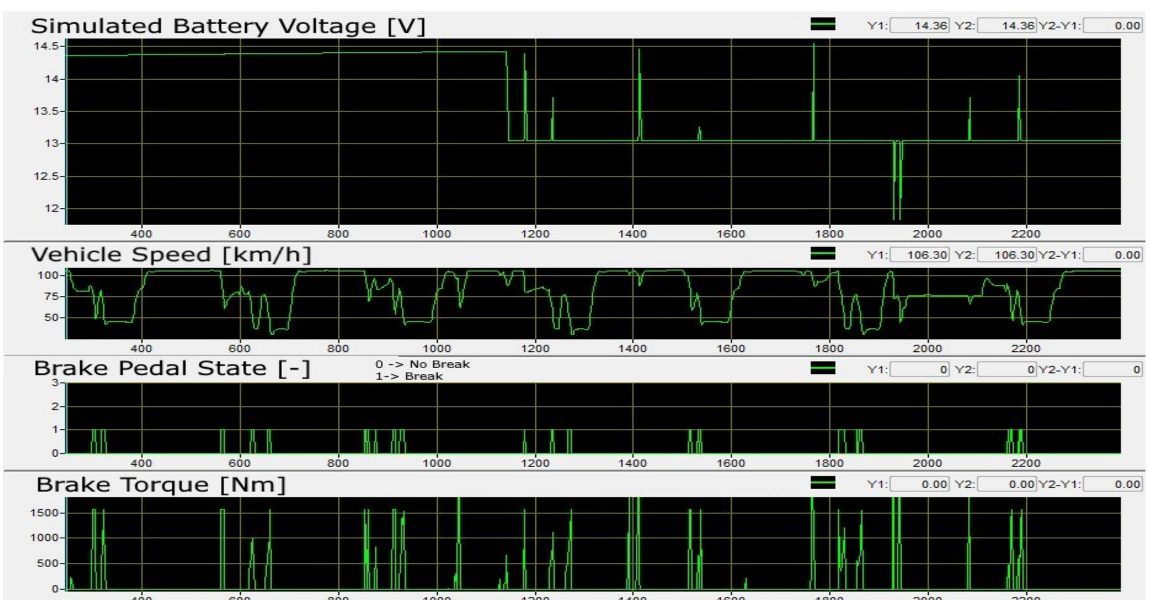


**Fig.6 Output of the simulated on-board voltage on the test bench**

# 5 Summary

Within the scope of this paper, a prototype for the simulation of the vehicle electrical system voltage was developed for a HiL test bench (Req. 4). It was not possible to use traditional approaches to simulate the on-board power system voltage, since no direct data on the consumers and suppliers from the on-board power system are available, due to data privacy. Instead, a new approach was developed that depends entirely on measurements from a test vehicle (Req. 1). State of charge detection by a learned classifier is used to generate an average voltage using a battery model. By introducing a learned classification, this can be done without prior knowledge of the system (Req. 3). Short term changes are detected and generated from the state of charge separately. By adding the mean voltage and the short-term changes, a realistic curve of the on-board voltage is generated. The voltage generated from the measurements using this approach does not match the voltage measured by the test vehicle exactly, but it has sufficiently similar characteristics for the test bench (Req. 2). A better battery model could be used, to increase the accuracy and added to the dynamic changes. The real-time execution of the approach was demonstrated with the implementation on the test bench (Req. 5). Thanks to the modular design, individual parts can be improved in the future to achieve even more realistic behaviours (Req. 6).

**References:**


[1] TRAUB M, VOGEL H, SAX E, *et al*. Digitalization in automotive and industrial systems [C]// 2018 Design, Automation & Test in Europe Conference & Exhibition (DATE). 2018: 1203.

[2] Maurer M, Gerdes J C, Lenz B, et al. Autonomes Fahren[C]. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015.

[3] Hesse B. Wechselwirkung von fahrzeugdynamik und kfzbordnetz unter berucksichtigung der fahrzeugbeherrschbarkeit [D]. Duisburg, Essen: Universitat¨ Duisburg-Essen, 2011. https://d-nb.info/1019930128/34.

[4] Wohlfahrt C. Von systematischer absicherung zur digitalen erprobungsfahrt[Z]. Stuttgart: 2016-10-27.

[5] WANG C, WINNER H. Overcoming challenges of validation automated driving and identification of critical scenarios[C]// 2019 IEEE Intelligent Transportation Systems Conference (ITSC). IEEE, 102019, 2019: 2639.

[6] KOBER C. Stochastische verkehrsflusssimulation auf basis von fahrerverhaltensmodellen zur absicherung automatisierter fahrfunktionen [M]. Wiesbaden: Springer Fachmedien Wiesbaden, 2019.

[7] KING C, RIES L, KOBER C, *et al*. Automated function assessment in driving scenarios[C]// 12th IEEE Conference on Software Testing, Validation and Verification. ICST, 2019: 414.

[8] REIF(Hrsg) K. Bosch grundlagen fahrzeug-und motorentechnik [M]. Wiesbaden: Springer Vieweg, 2017. http://www. springer.com/ series/12435.

[9] Heinemann D. Strukturen von batterie- und energiemanagementsystemen mit bleibatterien und ultracaps [D]. 2007.

[10] BUCCOLINI L, RICCI A, SCAVONGELLI C, *et al*. Battery management system (bms) simulation environment for electric vehicles [C]// 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC). Piscataway, NJ: IEEE, 2016: 1.

[11] YAN Q, WANG Y. Predicting for power battery soc based on neural network[C]// Proceedings of the 36th Chinese Control Conference. Piscataway, NJ: IEEE, 2017: 4140.

[12] BUCHNER S. Energiemanagement-strategien fur elektrische energiebor-dnetze in kraftfahrzeugen. Dresden: Cuvillier Verlag, 2008. https://depositonce. tu-berlin. de/bitstream/ 11303/ 1740/1/Dokument{ }51.pdf.

[13] BAYER S, WOLF M, KREUZINGER T, *et al*. Effektive Security-Tests am HiL-System[EB/OL]. 2016. https://www. researchgate. net/publication/318210163 Effektive Security-Tests am HiL-System.

[14] GUDER N. Dynamische bordnetzsimulation [J] Porsche Engineering MAGAZIN, 2015, 2.

[15] RUF F. Auslegung und Topologieoptimierung von spannungsstabilen Energiebordnetzen [D]. Munchen: Technische Universitat¨ Munchen, 2015. http://mediatum.ub. tum.de/? id=1220402.

[16] REIF K. Automobilelektronik[M]. 5th ed. Springer Vieweg, 2014.

[17] FABIS M R. Beitrag zum Energiemanagement in Kfz-Bordnetzen[D]. Berlin: Technischen Universitat Berlin, 2006. https://depositonce. tu-berlin. de/bitstream/11303/ 1740/1/ Dokument{ }51.pdf.

[18] BROY J. Modellbasierte entwicklung und optimierung flexibler zeitgesteuerter architekturen im fahrzeugserienbereich [D]. Karlsruhe: Universitat Karlsruhe, 2010. https: // publikationen.bibliothek.kit.edu/1000021274.

[19] ACHAIBOU N, HADDADI M, MALEK A. Lead acid batteries simulation including experimental validation [J]. Journal of Power Sources, 2008: 185(2): 1484.