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Testing Advanced Driver Assistance Systems for Fault Management with the VEHIL Test Facility

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This paper presents a methodological approach for validation of advanced driver assistance systems (ADASs), especially concerning fault management. Tools in this methodology are the unique VEhicle-Hardware-In-the-Loop (VEHIL) test facility and the associated simulation tool PRESCAN. With VEHIL the development process and more specifically the validation phase of intelligent vehicles can be carried out safer, cheaper, more manageable, and more reliable. In VEHIL a complete vehicle is tested in the simulation loop, such that the safety and reliability of an ADAS can be tested to great accuracy and reliability.

Topics/ Driver Assist Systems, Collision Avoidance & Pre-Crash Management, Modelling and Simulation Technology

1 INTRODUCTION TO ADVANCED DRIVER ASSISTANCE SYSTEMS

1.1 State-of-the-art ADASs

With the increasing demand for safer passenger vehicles, the development of advanced driver assistance systems (ADASs) is a major research topic in the automotive industry. An ADAS uses environment sensors (e.g. radar, laser, vision) and electronic control functions to improve driving comfort and traffic safety. It may assist the driver in reacting to dangerous traffic situations and even avoiding collisions. State-of-the-art examples of ADASs that have already been introduced to the market are adaptive cruise control (ACC), collision warning and avoidance systems [5], and pre-crash sensing systems [2].

1.2 Challenges in the development of ADASs

The demand for safety and reliability naturally increases with increasing automation of the vehicle's driving task, since the driver must be able to fully rely on the ADAS. Failure of an automatic safety system simply cannot be tolerated, e.g. autonomous emergency braking should be executed if, and only if, a collision is imminent.

Unfortunately, in contrast with these high requirements the growing number and integration of intelligent vehicle control systems causes an increasing complexity of the control architecture.

1.3 Need for new tools and methods

Manufacturers thus face conflicting requirements, but also increasing costs and a desire for a shorter time-to-market of their products. Not only the *design*, but also the *validation* of ADASs, especially regarding safety and reliability, therefore requires a growing effort.

To improve the control system design, measures such as redundancy and fault-tolerant control systems can be implemented in an ADAS. In practice, it is however difficult to define the requirements, choose the right measures and to validate their effectiveness. Currently, simulations and prototype test drives on a test track are used to validate an ADAS, but they are either not very reliable or too costly. It may therefore become impossible to evaluate an ADAS with guaranteed measures for the level of performance, safety, and reliability.

An *efficient* methodology and new design tools are therefore required for the validation of ADASs. For this purpose TNO has developed the VEhicle-Hardware-In-the-Loop (VEHIL) facility, a tailor-made laboratory for testing intelligent vehicle systems, as presented in Section 2. The added value of VEHIL in the development of fault management systems is illustrated in Section 3. Section 4 then proposes a methodological approach for the design and validation of fault management systems for ADASs and the use of VEHIL as a tool in this methodology. Finally, Section 5 summarises the advantages of an integrated development process using VEHIL, and discusses the ongoing research activities.

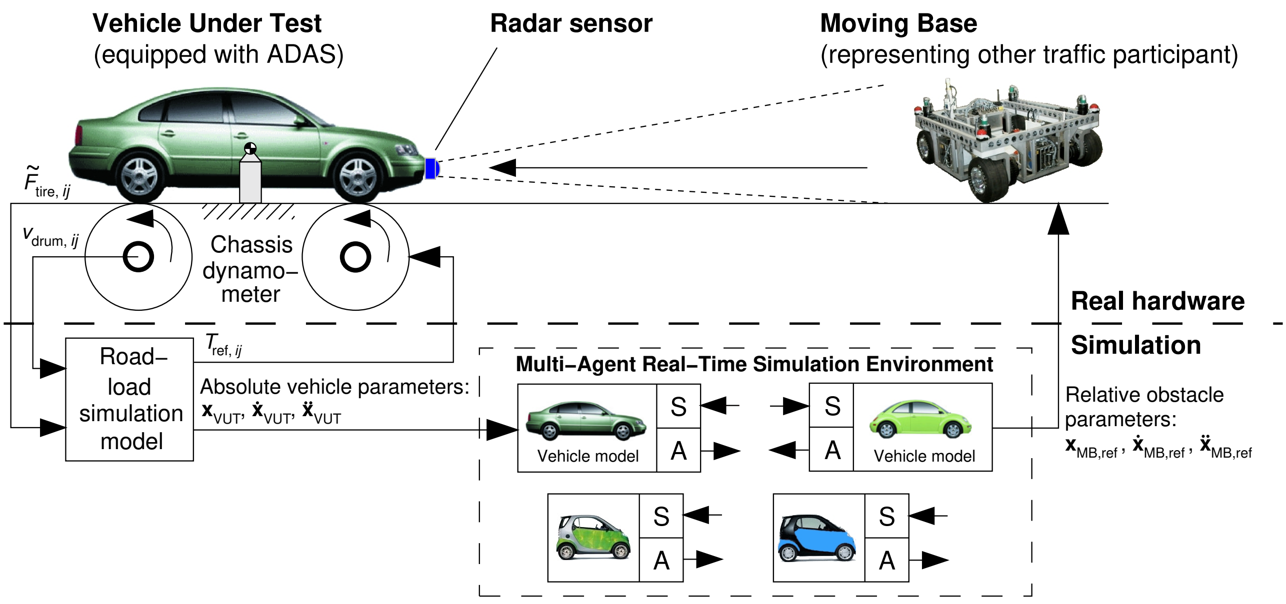

Fig. 1: VEHIL working principle.

2 INTRODUCTION TO VEHIL

2.1 Working principle of VEHIL

The VEHIL concept makes it possible to conduct experiments with full-scale intelligent vehicles in a laboratory, where only the *relative* motions between the test vehicle and other traffic participants are reproduced. For that purpose VEHIL relies on a multi-agent real-time simulation environment in which the vehicles, the infrastructure, and their interactions are simulated, as shown in the lower part of Fig. 1.

The so-called vehicle under test (VUT), i.e. the ADAS equipped vehicle, is mounted on a chassis dynamometer with four independent drums that provides a realistic load T for the vehicle's actuators (throttle, brake). This dynamometer measures the speed $v_{\text{drum},\,ij}$ of every wheel, where the subscripts i and j indicate the front or rear axle, and the right or left wheel, respectively. It also makes an estimate $F_{\text{tire},\,ij}$ for the tire force acting on every wheel. Using a road-load simulation model the reference torque $T_{\text{ref},\,ij}$ for every drum is calculated.

This road-load simulation model also reconstructs the VUT's *absolute* state vector $\mathbf{x}_{\text{VUT}} = \left[\begin{array}{ccc} x & y & \psi \end{array}\right]^T$, and its derivatives $\dot{\mathbf{x}}_{\text{VUT}}$ and $\ddot{\mathbf{x}}_{\text{VUT}}$, where (x,y) is the absolute position, ψ the orientation, $\dot{x}$ the velocity v and $\ddot{x}$ the acceleration a. Through the interface with the corresponding vehicle model in the simulation environment, the VUT's states are then changed for the next simulation step of the traffic simulation. From the defined interactions (through virtual sensors S and actuators A) between road users in the simulation environment the position of the VUT relative to the other road users, i.e. the *relative* state vector, can be calculated.

One or more surrounding traffic participants are selected to be represented by so-called moving bases (MBs) [8]. The MB is a 4-wheel driven, 4-wheel steered robot vehicle (see Fig. 2) that responds to position commands of the traffic simulator and carries out the relative motions to the VUT. The VUT's environment sensor then in turn monitors the MB motion and the controller receives input from the sensor as if the vehicle is actually driving on the road. Hence the experiment is a *closed-loop* hardware-in-the-loop simulation. Fig. 1 illustrates this working principle and Fig. 3 shows the corresponding laboratory setup. For more detailed information on the operation of VEHIL, the reader is referred to previous papers on this topic [1, 6–9].

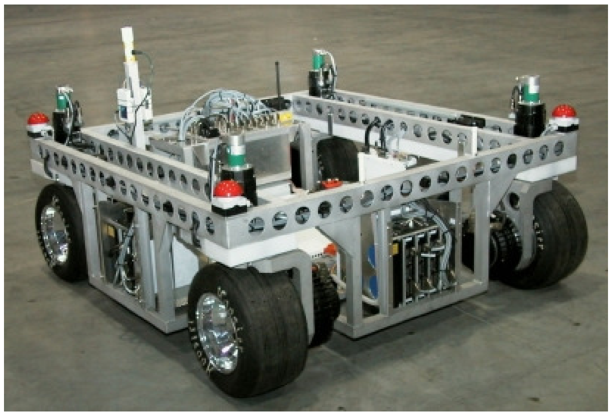

Fig. 2: The moving base.

2.2 ADAS applications in VEHIL

VEHIL is located in Helmond, The Netherlands, and is operational since November 2003 as an independent test facility for the evaluation of ADASs. Several types of ADASs can be tested:

- ACC and Stop & Go systems, see Fig. 6(b).
- Collision warning and avoidance systems, see Fig. 3.
- Vehicle-to-vehicle communication systems.

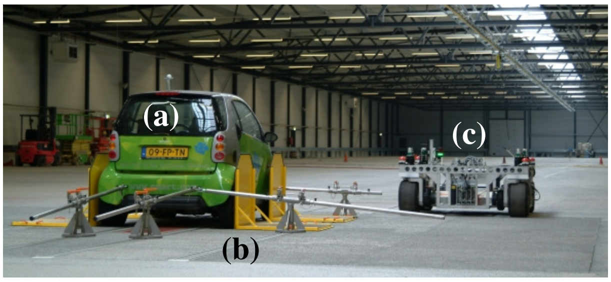

Fig. 3: VEHIL laboratory setup: (a) VUT equipped with a collision warning and avoidance system; (b) chassis dynamometer (beneath the floor) and (c) moving base.

- Collision mitigation and emergency braking systems.
- Pre-crash sensing systems, a VEHIL test of which is presented in [2].
- Blind spot monitoring systems.
- Night vision systems.

The chassis dynamometer of VEHIL can accommodate a wide range of vehicle types: apart from passenger vehicles, also trucks, busses, and fully automatic guided vehicles for passenger or cargo transport can be tested. Furthermore, VEHIL is suited for obstacle detection systems based on radar, vision or laser sensors.

2.3 VEHIL test objectives

VEHIL offers an added value in several steps of the development process of an ADAS:

- Sensor system calibration.
- Validation of sensor and vehicle models.
- Testing sensor post-processing and vehicle control algorithms.
- Optimisation studies, e.g. determining optimal sensor configuration and controller tuning.
- Validation of the integrated system, in terms of the nominal performance and driving comfort.
- Testing the system limits in safety-critical situations.
- Testing ADASs for robustness and fault management.
- Benchmarking, e.g. comparison of different control algorithms or sensor systems.

The following sections illustrate some of these test objectives.

2.3.1 Sensor calibration

Calibration of the sensor performance is necessary to decide if a particular sensor system meets its specifications. For this purpose, VEHIL provides an accurate reference on the obstacle position during the test in real-time, where the obstacle is the MB.

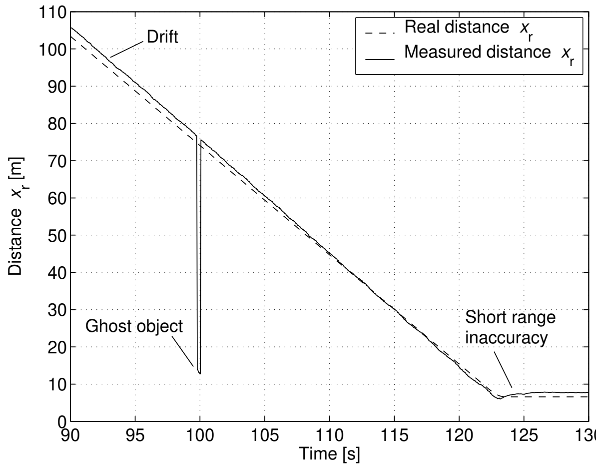

Fig. 4: Example of a radar sensor calibration test, highlighting some interesting sensor characteristics.

From a sensor calibration program typical sensor characteristics and possible sensor faults can be investigated. Typical sensor characteristics are the detection range, field of view, and indications of its accuracy and resolution. In addition, information on detection delays, missed detections, and false detections (ghost objects) can be retrieved. An example of a dynamic sensor calibration test is shown in Fig. 4. This plot shows the MB approaching the sensor at a constant velocity. Since the MB position is accurately known, the drift, accuracy and reliability of the sensor signal can be easily determined.

Sensor calibration results are useful for sensor modelling and to discover the critical points on which to test the complete ADAS in a later development stage. Furthermore, the size, location and cause of any faults can be identified, and used as input for both the design and the validation of the fault management system.

2.3.2 Sensor model validation

Sensor models are used for designing and testing the sensor processing and control algorithms in an early development stage. For this purpose TNO developed the software tool PRE-crash SCenario ANalyzer (PRESCAN) that offers an integrated solution for reliable simulation of an intelligent vehicle, including its vehicle dynamics, sensors, and environment in many different scenarios [4]. PRESCAN and VEHIL use the same multi-agent simulation environment as a backbone, such that both tools are fully integrated.

The sensor and vehicle models from PRESCAN can be validated by comparison of simulation and VEHIL test results. The validation is reliable, since the underlying simulation environment executes *exactly* the same traffic scenario in both PRESCAN and VEHIL. Fig. 5 shows an example of radar model output data, which can be validated with calibration data, as was shown in Fig. 4.

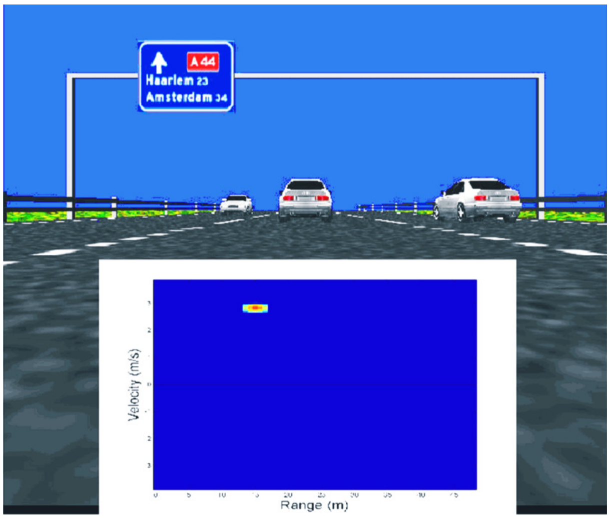

Fig. 5: Output of a radar sensor model, as simulated in the PRESCAN environment.

2.3.3 ADAS functional testing

Apart from testing the sensor separately, VEHIL offers the possibility for testing the complete intelligent vehicle, especially in extreme scenarios that would be too difficult or too dangerous to test on a test track. This is illustrated by Fig. 6, where an example is given of an ACC test, both in PRESCAN and in VEHIL. As indicated in Fig. 6(a), the ACC equipped vehicle (1) drives on the middle lane when suddenly a vehicle (2) cuts in from the right lane at a lower speed. As soon as the radar sensor on vehicle (1) detects the obstacle, the ACC algorithm activates the brakes. Vehicles (3) and (4) stay on the right lane and are used to test the ability of the radar for distinguishing important targets in the traffic environment (i.e. (3) and (4) should not be considered a target). On a test track it would be very difficult to safely and reproducibly carry out such a test with human drivers. In VEHIL however, the MBs can emulate a wide range of traffic scenarios in the relative world. The ACC scenario of Fig. 6(a) corresponds to the VEHIL laboratory setup of Fig. 6(b).

2.4 Added value of VEHIL in the development process

In summary, the VEHIL approach offers a number of distinct advantages compared to conventional design and validation tools:

- Costs are reduced, because only one prototype vehicle is needed and no test drivers are required. Furthermore, a large number of tests can be performed in a short time frame.
- Tests can be performed very safely, because no persons are physically present in the test area and because of the absence of high absolute velocities.
- VEHIL provides the opportunity for quick and flexible variation of the desired traffic scenarios.
- Because of the computer controlled environment, VEHIL experiments can also be performed in a more accurate and reproducible way than on a test track, while representing near-realistic operating conditions. All vehicle parameters can be easily monitored during the test. This facilitates investigating the influence of specific parameters and failure modes, which can be induced in the VUT, as will be discussed in Section 3.
- Finally, as illustrated by Fig. 7, VEHIL enables a better transition between simulations and test drives, which improves the efficiency of the development process in time and costs. Of course, outdoor test drives will always be necessary to evaluate the system's performance on the road. However, test drives can now be performed with a much higher confidence in the system, since the ADAS has already been thoroughly tested for a large number of scenarios with PRESCAN and VEHIL. VEHIL is thus *not* meant to substitute simulations and test drives, but to form an efficient link between them. The interaction between these tools is an important property that forms the basis for the methodological approach presented in Section 4.

(a)

(b)

Fig. 6: ACC test: (a) traffic scenario in PRESCAN and (b) in VEHIL.

3 FAULT MANAGEMENT SYSTEMS

3.1 Perturbations acting on ADAS

The operation of an ADAS controller is affected by several perturbations, as shown in Fig. 8(b). The *perturbation space* Δ (the combined set of possible failure modes and operating conditions) is composed of:

- Motions of other vehicles that are monitored by the sensor as the relative state vector $\mathbf{x}_r = \begin{bmatrix} x_r & v_r \end{bmatrix}^T$.

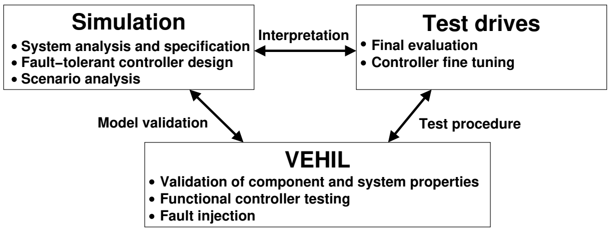

Fig. 7: The use of VEHIL in different steps of the development process of an ADAS, and its interaction with other validation tools.

- Disturbances, e.g. sensor noise and environmental disturbances.
- Modelling errors, since there is always a discrepancy between the real vehicle and sensor, and the models used for synthesising the controller.
- Faults acting on the sensor, actuator or vehicle components.

3.2 Fault management approach

Focussing on sensor faults as an example, the reliability of the control system can be improved by implementation of a fault management system, schematically represented in Fig. 8(b). Many different approaches for fault management exist, see [3] for an overview. Here we only present a basic scheme of a fault management system design, since the focus of this paper is on its *validation*.

One approach for fault management is the use of a vehicle state estimator. The difference between the measured signals $\mathbf{y}$ and the estimated signals $\hat{\mathbf{y}}$ is then calculated and expressed in residual signals. These residuals are subsequently evaluated by fault detection and identification logic, and in case a fault is detected appropriate action can be taken. Possible actions are changing the control objective or switching to redundant components. Alternatively, the vehicle can be degraded to a safer state, e.g. a speed limitation or a warning to the driver that the system is malfunctioning.

3.3 Fault injection in VEHIL

Fault injection means inducing faults in a system to measure its response to those faults, and to give a measure for the level of fault tolerance of the system. In VEHIL faults can be injected from the simulation environment and by physical injection in a controlled and reproducible way. Traffic disturbances can be introduced by MB motions; sensor disturbances can be introduced by adding a simulated signal to the physical input of the controller; alternatively, sensor disturbances can be introduced physically by environmental disturbances. Fault injection can thus be used to determine the effect of a single fault or a combination of faults under specific conditions, and to assess the overall effectiveness of the implemented fault tolerance mechanisms.

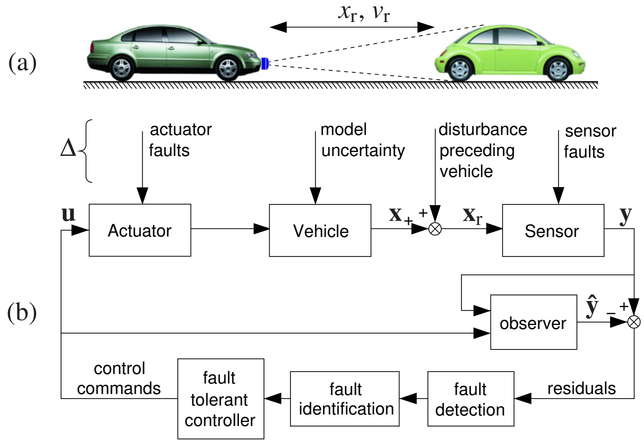

Fig. 8: (a) ACC measuring the distance x_r and relative velocity v_r to an obstacle; (b) schematic layout of a fault management system.

4 METHODOLOGICAL APPROACH FOR TESTING ADAS

A major problem with the validation of ADASs, is that the system cannot be tested *exhaustively* for every fault type under every operating condition. A validation methodology should therefore provide a suitable test program in order to sufficiently (but also efficiently) cover the entire perturbation space. To this aim we propose an iterative approach consisting of the following steps.

1. **Perturbation space identification** Firstly, the perturbation space has to be identified using sensor calibration and preliminary VEHIL tests. In addition, evaluation criteria are needed to judge how good the system performs under the influence of faults and disturbances. The performance and the corresponding criteria are grouped in the performance vector ρ. For a fault management system ρ can be defined in terms of the false alarm rate, missed alarm rate, and detection delay.
2. **Modelling** Next, a simulation model of the vehicle, its sensor system, and its control system has to be designed. For this purpose, models from the PRESCAN libraries can be adapted.
3. **Simulation** This model is then simulated in PRESCAN for controller design and analysis, and to identify interesting areas of the perturbation space Δ. Fig. 6(a) shows a visualisation of a traffic scenario simulated in PRESCAN. These PRESCAN scenarios can be generated in a randomised approach (e.g. Monte Carlo), such that a *representative* part of the perturbation space is covered. The simulation phase results in estimated measures for the performance $\hat{\rho}$ with respect to the criteria defined earlier. The reason that we prefer a *probabilistic* approach, is because a worst-case analysis on a control system is often too conservative, since several critical perturbations may be mutually exclusive. Furthermore, a conservative control system design will often limit the functional performance of the ADAS.

The probabilistic measure $\hat{\rho}$ is however always associated with certain level of reliability, since there is a small change that a worst-case scenario will occur. The reliability of $\hat{\rho}$ then depends on the number of simulations and the selection of the scenario set. One may therefore argue that a probabilistic analysis does not *prove* that the system is safe or reliable. However, conventional test methods for ADASs (such as test drives) are also based on a probabilistic analysis, since a test program always has a limited coverage. From a practical point of view, we therefore allow a probabilistic approach.

4. **VEHIL** The estimate $\hat{\rho}$ is however only reliable if the simulation models used are validated. Fortunately, the reliability of $\hat{\rho}$ can be improved with VEHIL tests. Therefore, the most interesting samples of the perturbation space Δ_i are chosen to be reproduced in the VEHIL facility, also in a randomised approach to efficiently cover Δ. These scenarios can be identified using thresholds for the performance criteria or when the reliability of the simulation model for this particular Δ_i is questionable.

   Simulations are thus not only useful in the early stage of ADAS development, but also for aiding the design of VEHIL experiments. During VEHIL tests faults can be introduced in a controlled and reproducible way, thereby achieving a better estimate $\hat{\rho}$.

5. **Model validation** When a limited set of VEHIL scenarios have been executed, the test results for VEHIL and PRESCAN can be compared. This model validation can provide information on necessary model improvements. In addition, $\hat{\rho}$ may indicate necessary improvements in the system design.

6. **Performance measure** In an iterative process the simulation results in step 3 and thus the estimate $\hat{\rho}$ can be improved. Subsequently, the VEHIL test program in step 4 can be better optimised. From the combination of simulation and VEHIL results the performance $\hat{\rho}$ of the ADAS can then be estimated with a high level of reliability.

5 CONCLUSIONS AND ONGOING RESEARCH

The concept of VEHIL and an overview of its applications has been presented. Furthermore, it was shown that VEHIL has an added value in several phases of the development process of an ADAS. VEHIL also enables a better transition between other validation tools (simulations and test drives), which improves the efficiency of the development process in time and costs. The added value of VEHIL thus lies in the fact that tests can be performed in an efficient and controllable way. Furthermore, the methodological approach presented in this paper provides a guideline for carrying out a suitable test program for validation of the ADAS for safety and reliability.

Ongoing research is focussed on extending the limits of the VEHIL facility with respect to various applications of intelligent vehicle systems. Especially testing these ADASs for fault management by inducing faults is subject of current investigation. In addition, a mathematical basis for the probabilistic validation approach, using randomised algorithms, is designed to formalise the guidelines for ADAS validation and to reduce the number of necessary tests.

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