How to Conduct Experiments With a Real Car? Experiences and Practical Guidelines

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Abstract. Higher computational power, new dimensions of interconnectivity and modern machine learning techniques are necessary for building a fully autonomous car, but exhibit an enormous technical complexity. Research about new approaches and technology for handling this complexity raises a problem: On the one side, researchers advocate transitions and replacements for the current systems mainly without deploying them in real cars on the streets. On the other side applying theoretical approaches without clear evidence of their practical benefits is risky for the practitioners. As a solution to close this gap, researchers should bring their ideas more often into physical cars and support their proposals with measurements from realistic experiments.
With this paper, we share our insights from an academic perspective about connecting scientific prototypes with a real car. (1) We discuss three interface designs for setups with differing connectivity to a running car; (2) We provide a checklist for planning and organizing real car experiments including a discussion of involved trade-offs; (3) We give practical advice and identify best practices learned from our own experiments inside a car. In sum, we demonstrate that even with a short budget and a small team size it still is possible to bring prototypes into real cars.

Keywords: Automotive · Car Interface · Experimental Evaluation

1 Introduction

The automotive domain is in the process of a huge technological change for turning a vehicle from a basic machine into a fully autonomous transport mean with included infotainment systems [3]. Although academic research and industry both work towards the same goal, there is a gap between academia focusing on new ideas and approaches, whereas industry must naturally focus on the most promising and applicable ideas [11].

As an academic research team in the area of Software and Systems Engineering, we have developed various new algorithms and approaches for modern cars in the last years. These software prototypes span from profiling of driving scenarios to different approaches for intrusion detection. However, we have ended up with the same problem in all these prototypes: They cannot be evaluated realistically without being used inside a real car. Nevertheless, putting research prototypes into a car has seemed risky, expensive and a plenty of work.

We are aware of various work from bigger research teams, ranging from building their own car [8] to collaborations between multiple universities [7]. Such projects, budgets and team sizes were not available for us, but still we aimed for a realistic evaluation. Through various iterations we experimented with different approaches and realized several experimental setups: Starting with small dongles for passive data-recording, over Raspberry Pis with acoustic feedback to the driver, to partially controlling the car's driving behavior through attacks with a connected laptop. In retrospective all these experiments are based on the same decision process and follow the same schema in approaching a car.

In this work, we summarize our experiences from experiments with real cars under tight budget and human resource constraints. Based on practical advice, guided by checklists and best practices, we advocate experiments with cars while keeping the risk controllable and the budget and workload low. Thus, our paper dedicated to small research groups complements the already documented effort of bigger research teams and projects. Thereby, we want to demonstrate that our initial concerns as a small team were not justified, and we hope to encourage academic researchers to put their experimental prototypes earlier and more often into real cars. Thus, we make an important step away from pure paperwork and artificial toy setups, towards real systems. Consequently, all research findings have higher significance and provide meaningful validation of the new approaches.

During this paper we use several terms that we define as follows: The implemented research prototype that is designed for operating with a car is labeled as an *experimental setup*. An *experiment* is the process to collect empirical data with the experimental setup. *Research team* refers to all people taking part in the planning and conduction of the experiment. The *track* is the physical location where the car is driven during an experiment. Finally, *conducting an experiment* denotes all the required steps for getting results from the experiments—from planning and organizing, to driving the car to elicit data.

2 Constraints and Requirements

Due to their dependency on expensive and potentially dangerous equipment, experiments with real cars are strictly limited by external factors. In the following discussions about decisions made before and during experiments, we distinguish between constraints and requirements: *Constraints* identify the general limitations that are invariant for all experiments. These constraints are imposed by rationality and by good scientific practice. *Requirements* on the experiment are based on specific trade-offs and vary in different usages. All requirements reflect the affected constraints, but are influenced by decisions of the research team.

2.1 Constraints

Assured Safety: During the experiments, no human must be harmed. Damage to the car or used setups might be acceptable but should be avoided if possible. Therefore, it must be assured that the used setup is controllable at all times and in all circumstances.

Minimal Budget: The cheaper the conduction of an experiment is, the better. It is impossible to avoid some minimal costs, but if there are two approaches with comparable outcome, the cheaper approach is preferable.

Sound Documentation: After the experiment, the documentation of the used setup, and all collected data need to be as comprehensive and complete as necessary for supporting or rejecting the hypothesis. The experiment needs to be reproducible in the future, and the data is required as proof for the results and support for the conclusions.

2.2 Requirements

Acceptable Risks: While working with physical hardware, it is impossible to avoid all possible risks and dangers. However, it is important to consider which scenarios are acceptable and which are not. There is no guarantee or full insurance. Therefore, all parties involved during the conduction need to agree on the maximum acceptable risk during the experiments. This especially applies if regular traffic participants are involved, as no additional risk can be put on them.

Available Budget: The physical car, the experimental setup as well as the track and the used equipment cost money. With smart ideas, there are often strategies that reduce costs and enable low budget setups. Some of these tips will be highlighted during this paper.

Usage of the car: At the beginning of the experiment planning, it is important to consider what to actually do with the car. This includes the driving scenarios as well as how the experimental setup interacts with the car. Since the researchers can focus only on relevant aspects, this offers big space for decisions.

3 Candidate Interfaces between Setup and Car

For putting an experimental setup into the car, the first decision is about the interaction with the car. The information exchange is highly dependent on the experiment, but for the interfaces, in general, there exist three different choices depicted in Figure 1 and discussed in this section. Hybrids and combinations of these interfaces for different parts of the setup are also possible.

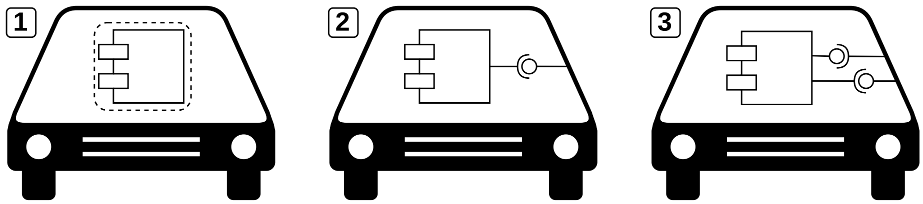

Fig. 1. Three interfaces for experiments: (1) Isolation, (2) Receiving, (3) Interaction

3.1 Isolation of setup and car

A simple approach is not to connect the experimental setup with the car at all. Just through operating inside the car and driving around with the setup already enables several experiments. Various sensors like cameras, gyroscopes, or GPS dongles enable a realistic data collection without direct connection to the car.

When the experimental setup is completely isolated from the car, the only risk results from a potential interaction with the driver. The setup will behave inside the car exactly as it does during the preparation, and the operation of the car is not influenced at all. However, the isolation might require using redundant sensors, which is more expensive than reusing the sensors inside the car. Furthermore, the usage of the car is limited as the setup is never connected with any network or realistic data from the car. For example, this type of interface has been used to collect GPS traces around a city area to improve privacy issues [4] and several variants to detect driver fatigue [10].

3.2 Receiving data from the car

Another approach for an interface is to connect the experimental setup with the car, but only to receive information out of the network through the On-Board Diagnostic (OBD) [9]. This standardized interface provides access to various information from the vehicle, especially the engine, for example, the current speed, the driven distance or the engine's intake and exhaust.

As the OBD-port is designed for receiving information during the operation of the car, the risk of this approach is rather minimal, when the experimental setup is robust against delays or gaps in the received information. There exist diverse OBD-adapters and—due to the standardization—they are rather cheap. For example, this type of interface has been used to determine the fuel consumption in osculating traffic [12] and to analyze the driving behavior to spot unsafe driving [1]. Unfortunately, OBD does not offer access to advanced sensors as video streams, lidar or radar. For receiving such data, the approach described for interaction between setup and car is also applicable for just listening to the network. However, it remains more intrusive so the provided assessment of this other approach still applies.

3.3 Interaction between setup and car

The most intrusive interface is an integration into the car's network for directly receiving, sending and even suppressing messages. The vehicle does not openly provide such an interface, but from our experience, it is still accessible reasonably easy. After removing the interior lining—often through basic click mechanisms—many cables are tangible. For instance, behind the rear mirror or under the central console are convenient choices that expose various networks and do not impede the driving. The concrete layout differs between manufacturers and car models, but in our case, the information was always easily accessible online.

Such an interconnection with the experimental setup is very dangerous, if the setup is not tested thoroughly and carefully. Wrong network interactions can potentially disable or permanently destroy the car's electronic components. Therefore, this approach has two major prerequisites: First, the setup needs a physical connection to the relevant network in the car. Most cables inside the car have standardized plugs that are cheaply available, but the concrete connector might still need to be handmade or at least customized. Second, the setup needs to understand the network protocol and the relevant payload in order to communicate with syntactically valid and semantically meaningful messages. Although the full message matrices are kept confidential by the manufacturers, there exist open communities trying to reverse engineer the networks, for example, the opendbc project [2] for CAN. Overall, the available information from the network as well as the potential to integrate the experimental setup directly into the car enables a huge potential for use cases, that might be worth the implied risk and effort to establish this interface. For example, this type of interface has been used for excessive security penetration testing [6] and to develop extensible prototypes for autonomous driving [5].

4 Checklist of Organizing Experiments

After the experimental setup is prepared and provides a suitable interface to the car, the concrete experiments need to be organized. This section discusses the most important questions for devising the experiments. Each question refers to requirements introduced in Section 2 and provides multiple alternatives with different degrees of risk, budget, or usage of the car.

4.1 How to compose the research team? (risk, budget, usage)

Some experimental setups can be operated by a single person—the driver of the car. For keeping the risk defensible with this, the experimental setup needs to be very automatic and should only require close to no interaction by the driver. So, this is only an option if the experimental setup mostly collects data while not interfering with the drive. With experiments that require at least some interaction or control during the drive, having two researchers in the car is reasonable to keep the risk manageable without full automation: one for focusing on driving the car and the other for controlling the experimental setup.

If the experiment requires equipment or observations from outside the car, adding a third person to the team might be reasonable to assist with the setup or to focus on documentation. Such assistance is comfortable, but from our experience, stationary cameras permanently recording are also a suitable alternative. Additional people watching the experiment could be distractive and disturb the focus. Therefore, too many people should be avoided as they also imply a safety risk during the experiment.

4.2 Where to get a suitable car? (budget, usage)

Only if the usage requires a permanent modification to the car that cannot be undone without damage, then buying a car is the only option. Without these, there also exist cheaper alternatives. If the usage scenario is not limited to specific cars or car models, mainly when the setup is in isolation from the car, big rental services are the best option as they offer cars for short periods and very small budget. If the experiment requires a specific car model, for example, because of some sensors incorporated in an interactive interface, big rental services to our experience do not provide a broad choice between distinctive car models.

However, there also exist various smaller car and repair shops that have a fleet of cars for rental. Most of the time, they focus on a specific brand and offer all the recent models to similar conditions as the big rental services. After contacting a few shops in our surrounding, we were always able to find the model that we needed. No matter how the car is rented, it is crucial to check that the planned usage is legally permitted.

4.3 Where to do experimental rides? (risk, budget, usage)

Non-interaction setups with no major risk may just be driven on regular streets as the car still has a permission to operate there. Modified cars do lose their permission to operate on regular streets and need an isolated, private place to not endanger regular traffic. Furthermore, the specific driving scenario—the speed, traffic, maneuver—is limiting the useful types of location. Industry corporations, bigger research institutes or driving schools have specially designed tracks for test drives. If the research team has a more flexible time schedule, there are also options to build their own track on a private parking place. For example, the parking side of a university is crowded during the week, but on the weekend it is mostly empty. So with some barrier tape, parts of the parking places can be separated and used for the experiments. These separated tracks lack street signs or road markings, but the research team can build them. For the road marking, washable color or barrier tape fixed straight on the ground has worked the best for us. Street signs can be emulated with paperboard stabilized by water-filled plastic bottles. If the car detects obstacles through radar, in our experience wrapping the paperboard in aluminum is a simple solution. Nevertheless, separated tracks limit the usages as their length is limited, and the driving scenarios are monotonic.

5 Best Practices and General Advice

This final section provides general considerations for experiments with cars. Depending on the concrete experiment, this list is not complete, but it provides a baseline to prevent basic mistakes.

5.1 Structure the available time in advance

A clear structure of what to do is essential for assuring that the spent time leads to results. Therefore, the minimum is at least a temporal order of the concrete experiments. The most important part of the schedule is to agree on limits: This phase will end at this time, or during the experiments the car will not drive above this speed and not outside this area. Additionally, the schedule should consider breaks with snacks and food explicitly. It is important to get out of the car regularly as it is not comfortable to work with the laptop on the knees for longer hours. When the experiments—success or failures—bring strong emotions, these breaks are valuable to calm down again.

5.2 What if the setup does not work?

None of our experiments has worked on our first attempt. Often there were only small errors, but identifying them can be very time-consuming. Hence, it is important to include self-checks into the experimental setup, for example, if all the cables are connected properly. Also, a simple interface eases the experiments as for example fast and precise typing is problematic during drives with higher speed. Ideally, these interfaces also offer debugging options and provide meaningful error messages if something goes wrong. Last but not least, never try to hack something quick and dirty during the conduction. These hacks can influence the whole experimental setup, ruin all measurements and have severe safety impacts.

5.3 Enduring power supply

Especially conducting or preparing experiments in an idle car exhausts the batteries of the equipment as well as of the car. While there are external chargers for the car battery, these are expensive and there exist cheaper alternatives. In our cases, it was the easiest to find one member of our team that drove the car to his home and back to work in the morning. This procedure refilled the batteries and was sufficient for day long experiments.

The other equipment inside the car can use two different forms of power supply: When the component is running on batteries, bringing replacement batteries or a power bank is sufficient to operate during the day and to recharge during the night. Alternatively, the battery of the car can also be used to power the experimental setup. There exist various adapters for USB or laptops to the vehicle input and also the OBD-Port provides a small source of power.

6 Conclusion and Outlook

With this paper, we documented our experiences with connecting experimental setups with running cars. Starting with a refinement from general constraints to competing requirements, the report elicited three different interface designs to connect the experimental setup with the car. These requirements and interfaces are used as a foundation for a checklist of the organization and best practices for conducting the experiments. The car usage can vary from driving around with a small single-board computer to partially disassembling the car to connect new components. Although the implied risk cannot be avoided completely, the discussions provide guidance for keeping it controllable. A bigger budget is helpful, but with focus on the minimal realizations the overall budget can be cut down.

To balance conflicting requirements is difficult as long as the constraints and their implications remain abstract. Hence, this paper provides a foundation for discussions in the researcher team in order to decide about each aspect individually and eases the agreement about the shape of the experiment. Thereby, our checklists and best practices are a foundation for conducting academic experiments in various research domains.

We would like to end this experience paper with a personal comment: Before we touched a physical car, we expected it to be a big challenge to connect our experiments with a driving car. However, after we gave it a try it always turned out to be relatively easy. The insights that we gained from a few drives with our experimental setups changed our understanding completely. Sensor data and measurements of the real physical behavior and real inaccuracy; a real time operation and realistic information flow workload; and most importantly authentic interactions with the driver and the driving behavior, in combination spotted several misconceptions in our research prototypes and provided valuable validation. Therefore, we highly recommend that academic researchers more often aim for putting their research into a real car. With these guidelines we hope to provide enough support to encourage more researches to follow our direction and gain—as we did—richer and more applicable insights through their projects.

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A Key-Questions from the Paper in Condensed Form

A.1 Candidate Interfaces between Setup and Car

1. What kind of interaction from the setup with the car is required?
2. What sensor data does the setup require?
3. What makes the deployment inside a car different from without a car?
4. How does the driver interact with the setup?

A.2 Checklist of Organizing Experiments

1. Is there need for a co-driver to assist with the experiments?
2. Does the experiment require additional documentation, e.g. by an additional video from outside the car?
3. Is some special car model, e.g. with a specific sensor, required?
4. Does the car need to be permanently modified?
5. What characteristics need to be present on the street?
6. What interaction with other traffic participants is needed?

A.3 Best Practices and General Advice

1. Has the setup been tested extensively before the experiment?
2. Does the schedule contain regular breaks?
3. Does every experiment have limits (time, speed, location, etc.)?
4. Does the setup provide a debug interface?
5. Are there replacement batteries for the setup?
6. How is the battery of the car regularly recharged?