China's 12-Year Quest of Autonomous Vehicular Intelligence: The Intelligent Vehicles Future Challenge Program

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Abstract—In this article, we introduce the Intelligent Vehicles Future Challenge of China (IVFC), which has lasted 12 years. Some key features of the tests and a few interesting findings of IVFC are selected and presented. Through the IVFCs held between 2009 and 2020, we gradually established a set of theories, methods, and tools to collect tests' data and efficiently evaluate the performance of autonomous vehicles so that we could learn how to improve both the autonomous vehicles and the testing system itself.

*A*utonomous driving refers to using onboard cameras, lidar, and other sensors to perceive traffic environments, plan and make decisions about travel paths, control vehicle movement, and complete autonomous driving without human intervention. It is believed that autonomous vehicles are able to greatly enhance traffic safety and efficiency and reduce congestion and pollution. People without the ability to drive can also enjoy the convenience of this modern, high-tech transportation [1].

Recognizing that autonomous driving is a disruptive technological change to the traditional automotive industry, the Natural Science Foundation of China (NSFC) has identified automated vehicles as one of the key research and development endeavors to be supported by its Department of Information Science. Several research bases in China have made significant progress in autonomous vehicles under the major research plan, "Cognitive Computing of Visual and Auditory Information," supported by the NSFC. These primary research bases include, but are not limited to, (in alphabetical order) Beijing Institute of Sci-

ence and Technology, Beijing Union University, Chang'an University, Hefei Institute of Materials Research, Military Institute of Transportation, Nanjing Institute of Science and Technology, National University of Science and Technology, Shanghai Jiaotong University, Tongji University, Tsinghua University, Wuhan University, Xi'an Jiaotong University, and Zhejiang University.

Since 2009, the NSFC has sponsored 12 consecutive editions of the Intelligent Vehicles Future Challenge (IVFC) (see Figure 1). The main goals of these challenges include
- publicizing the importance of autonomous driving to society
- attracting and cultivating young talent interested in autonomous driving
- testing autonomous driving prototypes to improve them
- collecting a large amount of data for future study.

IVFC 2009 was held together with the IEEE Intelligent Vehicle Symposium 2009 in Xi'an, and IVFC 2018 was held together with the IEEE Intelligent Vehicle Symposium 2018
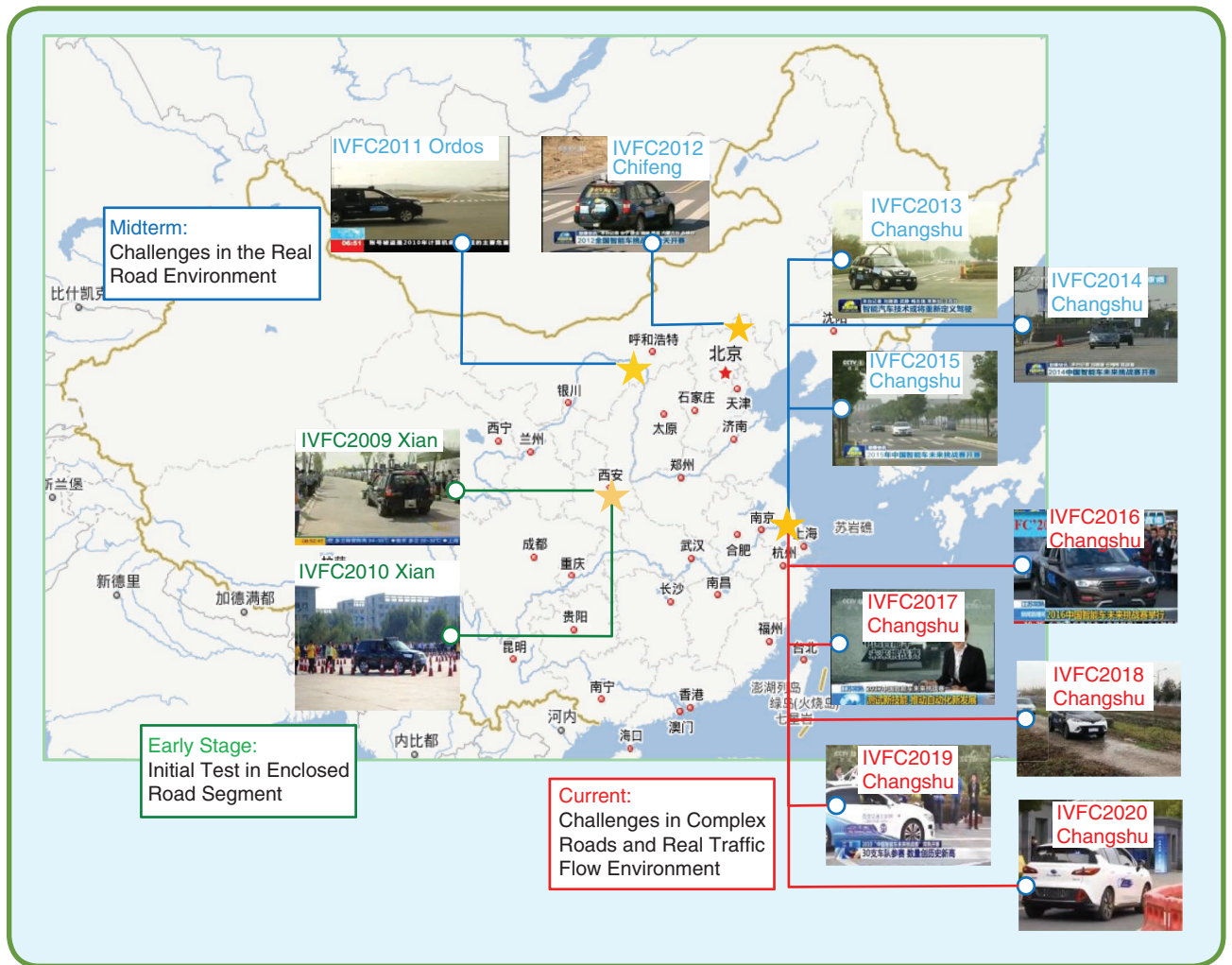
FIG 1 The locations and periods of IVFC (2009–2020).

FIG 2 (a) The opening ceremony of IVFC 2009 and (b) a demonstration of the intelligent vehicle test system at IVFC 2018.

in Changshu (see Figure 2). Many scholars from all over the world watched these two challenges and offered many useful suggestions to the organizers of IVFC.

The competing vehicles' autonomous driving tasks are becoming increasingly difficult, and the overall technical level is increasing. These challenges have strengthened the communication among research bases and have promoted the rapid development of China's autonomous vehicle research. More specifically, these challenges have triggered the research of testing standards, technologies, and methods for autonomous vehicles.

Accounts of the 2009–2020 Challenges

The first IVFC was held in Xi'an in 2009 (see Figure 2). Four autonomous vehicles took part in IVFC 2009, and only one could finish the 3.2-km test. In the first two IVFCs, the testing vehicles were required to correctly recognize some basic elements of the driving environments (e.g., road boundaries, lane boundaries, and traffic lights and signs). All of the tests were held in closed road segments. The challenge vehicles moved so slowly that the teams could walk alongside them to monitor them (as illustrated in Figure 3). These two IVFCs could be viewed as the "early stage" of IVFC.

Since the third IVFC, the testing vehicles have been challenged to appropriately interact with other traffic participants (e.g., an articulated pedestrian dummy and vehicles driven by testing engineers) in a partly open road environment. Since 2013, a new proving ground dedicated to intelligent (autonomous/semi-autonomous) and connected vehicles has gradually been built in Changshu, Jiangsu, China. All of the following IVFCs have been held with the support of this proving ground. This ground's critical area is a nine-patch grid divided by ordinary city roads, which are also used by nearby residents. Some intersections of this grid are equipped with advanced traffic signal control while the others do not have signals. Some cells of this grid are used to reproduce narrow country roads, as displayed in Figure 4. In the third IVFC, the challenge vehicles moved much more quickly, resulting in a need to design new methods to monitor them (an explanation is provided in "The Sensing System and Capabilities" section). The complexity of testing tasks was gradually increased to keep up with the testing vehicles' increasing capabilities. IVFC 2011 to 2015 could be viewed as the "midterm stage" of IVFC.

The elevated expressway ring road of Changshu was constructed in 2015, making Changshu the first county-level city to have a road of this kind. In IVFC 2016, we held the first expressway challenge for autonomous vehicles in China. China Central Television interviewed participants and broadcasted part of the challenge live. The concept of autonomous vehicles had begun to come to the forefront of Chinese people's minds. Expressway challenges for autonomous vehicles were also held from IVFC 2017 to 2019 (see

FIG 3 The early-stage IVFC (2009, 2010).

examples in Figure 5). The sensors seamlessly collected the real-time testing data acquired by each testing vehicle and the roadside and aerial cameras. The driving tasks became more complicated than those in the early-stage and midterm IVFCs, too. For example, in IVFC 2018, the testing vehicles were challenged to drive a long distance under viaducts or in tunnels to test their capability to recognize roads without the aid of GPSs. IVFC 2016 to 2020 could be viewed as the "up-to-date" stage of IVFC. The success of vehicles in expressway challenges marked the maturity of the data-collection and analysis system for autonomous vehicle testing.

The number of participants in IVFC continuously increased, from four autonomous vehicles and around 200 people in 2009 to 24 autonomous vehicles and more than 2,000 people in 2019 (displayed in Figure 6). It should be pointed out that the drop in participation of both autonomous vehicles and people in 2020 was directly caused by COVID-19. The testing mileages of vehicles has significantly increased since 2016, when we began to hold expressway challenges. We canceled the expressway challenge in IVFC 2020 as a result of the COVID-19 pandemic.

Some Details of the Challenges

The Tasks for Autonomous Vehicles
As illustrated in [2]–[4], there are two representative tests of autonomous vehicles: scenario-based tests and function-

FIG 4 The Changshu Intelligent Vehicle Proving Center.

ality-based (ability-based) tests. Scenario-based tests, such as the DARPA Grand Challenge and DARPA Urban Challenge [5]–[10], roughly characterize the scene but explicitly define the features of the driving environment and traffic participants. Functionality-based tests separately and independently address special functions (e.g., sensing/recognition) of autonomous vehicles separately and independently but often lack a comprehensive understanding of the vehicles' tasks.

To integrate them, we set up a semantic diagram for driving intelligence, as presented in Figure 7. In it, we highlight the test tasks as the previously missing links between scenario-based and functionality-based tests. A ve-

hicle needs to finish a series of tasks (activities that need to be accomplished within a limited period/spatial scope) to successfully pass any particular traffic scenario [11].

We can further categorize the semantic tasks into three kinds: sensing, decision, and action tasks. For example, understanding traffic lights belongs to the sensing tasks. Each entity (e.g., road, vehicles, traffic signs, traffic lights, and pedestrians) in the driving scenario is associated with three kinds of sensing tasks to determine the intention of the entity: a detection/recognition task atom, a tracking task atom, and an understanding task atom. Several decision tasks will be assigned for each entity depending on whether and how its movement will intervene with the testing vehicle.

FIG 5 The expressway challenge tests in IVFC using (a)–(b) human-driven interacting vehicles (c) and an autonomous vehicle (in the red circle).

Generally, we can further divide the decision tasks into five types:

- Keep the current driving state.
- Track a new leading vehicle.
- Change to free driving.
- Change lane.
- Slow down to stop at a position according to the decision results.

The action tasks are tightly associated with the decision tasks and are thus omitted here. Based on such a setting, our scenario-to-task decomposition process could establish a set of formal and standard language to describe the interactions between the testing vehicle and other entities in the studied driving scenario.

Figure 8 gives an example of generated semantic tasks for a particular driving scenario in which the action tasks are too simple and are thus omitted. The testing vehicle moves from west to east. It first needs to detect and identify the traffic light. It then must understand that the current traffic light is green, and that it does not need to slow down. Soon after that, the testing vehicle needs to detect and identify another vehicle (Vehicle A). Then, it must understand that Vehicle A has a higher priority to pass through
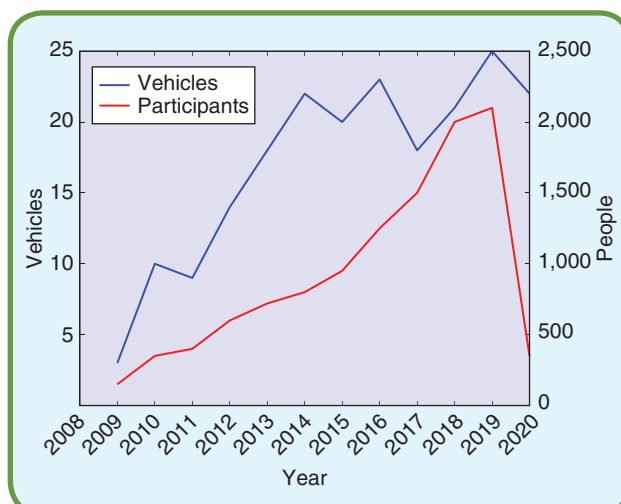
FIG 6 The numbers of participating autonomous vehicles and people at IVFC from 2009 to 2020.

the intersection, and it must slow down and stop before the stop line to avoid a collision.

Scenario-based tests address the scenario-task relationship on the left side of the semantic diagram in Figure 7.
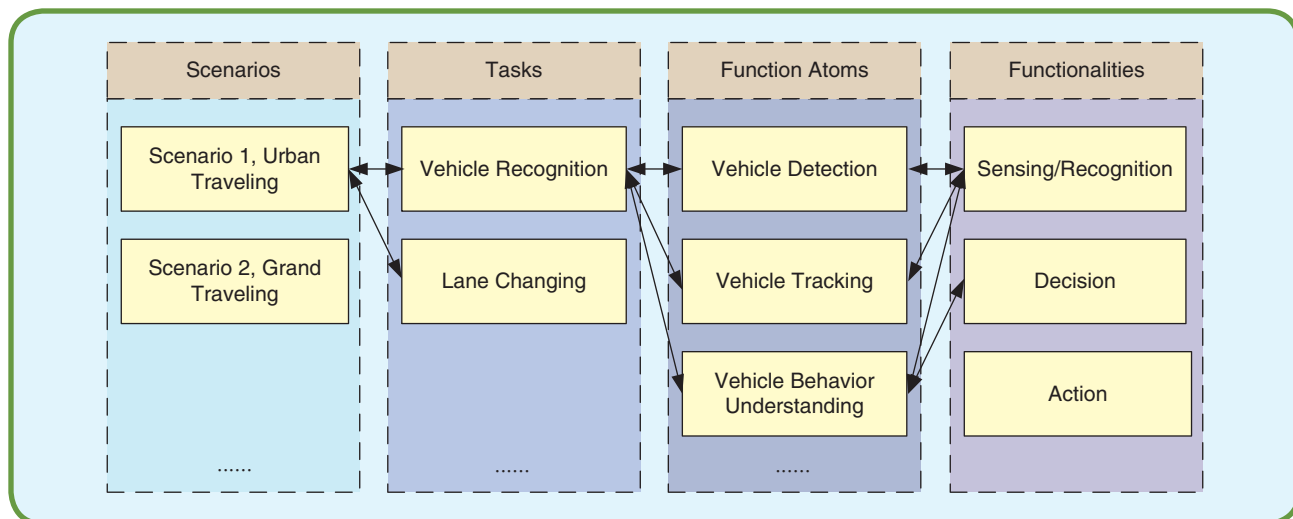
FIG 7 The semantic diagram of the driving intelligence of intelligent vehicles.
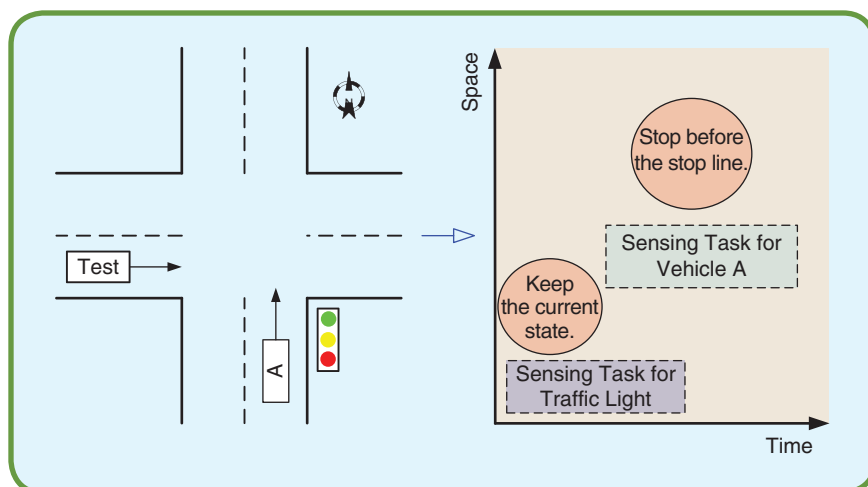

FIG 8 A temporal-spatial plot of the specified tasks for a given driving scenario.

In contrast, functionality-based tests focus on the task-function relationship on the right side. To generate particular testing scenarios for the challenge vehicles, we transverse from the right side of the semantic diagram to the left side, aiming to test some particular function atoms. We often linked several independent tasks along a particular path to save time and money and sequentially tested them in our challenges. For instance, a vehicle needed to finish 12 tasks in IVFC 2018, including 1) make a U-turn, 2) pass the signalized T-intersection, 3) pass through the tunnel in which GPS is blocked, 4) pass other vehicles, 5) pass the cross-intersection without signals, 6) recognize the stop sign dedicated for vehicles and behave appropriately, 7) pass the rural road, 8) give way to a pedestrian before U-turn, 9) give way to bicycle, 10) pass the working zone, 11) pick up passengers at a randomly selected position and return to a

specific point, and 12) park into the assigned berth. See Figure 9 for an illustration.

Usually, a vehicle will gain a certain score after it successfully finishes a particular task. If a vehicle makes some mistakes while finishing a task (e.g., slightly violates the traffic law by stopping after the line), its score will decrease. If human operators interfered to help a vehicle finish a task, its score would significantly decrease. To encourage more participants of IVFCs, we allow the challenge vehicles to remit a few tasks, but the scores of the remitted tasks will not be counted in their final scores. We also take travel time and a few other factors into account when calculating a challenge vehicle's final score. The vehicle that gains the highest score wins the championship.

The task complexity in each IVFC gradually increases. In the early-stage IVFCs, the challenge vehicles only needed to recognize driving environments (e.g., road lanes, curbs, cones, barriers, and traffic lights). In the midterm-stage IVFCs, the vehicles needed to be able to deal with some moving dummies that were used to simulate pedestrians suddenly rushing into the road. In the up-to-date-stage IVFCs, the vehicles must drive along with human-driven vehicles in both expressways and urban roads. In the recent IVFC in 2020, the vehicles were not restricted on a given path. Instead, they needed to find out the economic routes to serve as many simulated customers, who appeared in the preselected region, as possible, within a fixed time budget.

The difficulty of sensing tasks has noticeably been leveling up, as can be seen in Figure 10. In the expressway challenges of IVFC, the GPS signals are partly blocked out when the vehicles are under the elevated bridge. In the tunnel tests (in which we used long sheds to simulate tunnels), the GPS signals are strictly screened. Some challenge vehicles have not been able to drive in such situations since their location systems heavily depended on the GPS signals. The vehicles that succeeded in passing such tests needed to rely on their visual odometers and inertial navigation systems. It should be pointed out that, since IVFC 2019, some vehicles have been able to finish entire tests without any GPS sup-
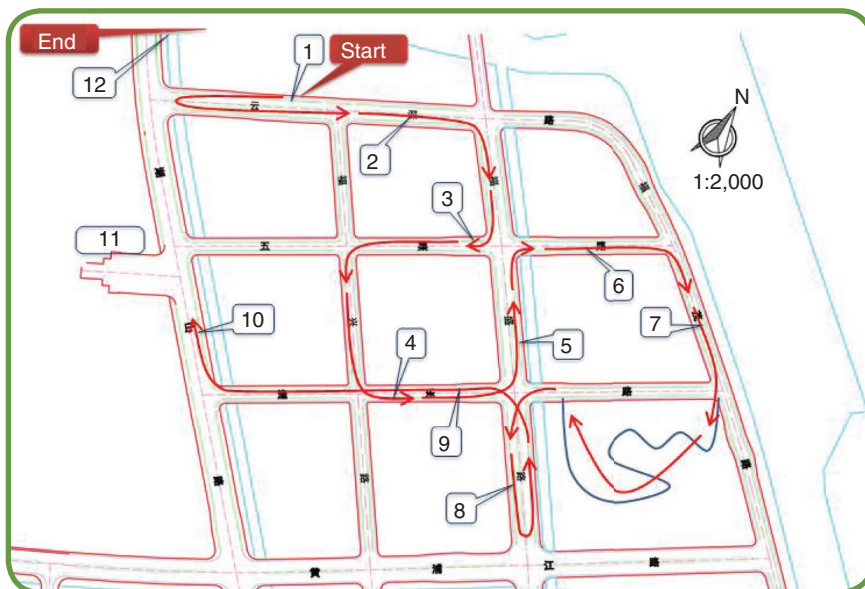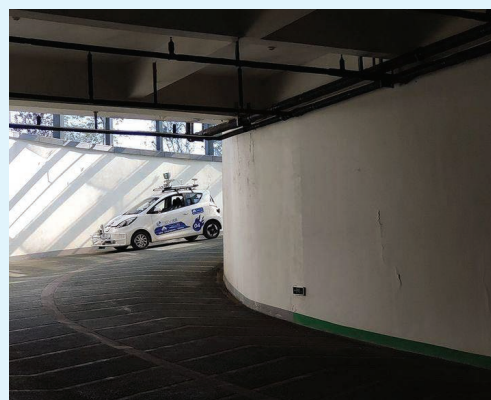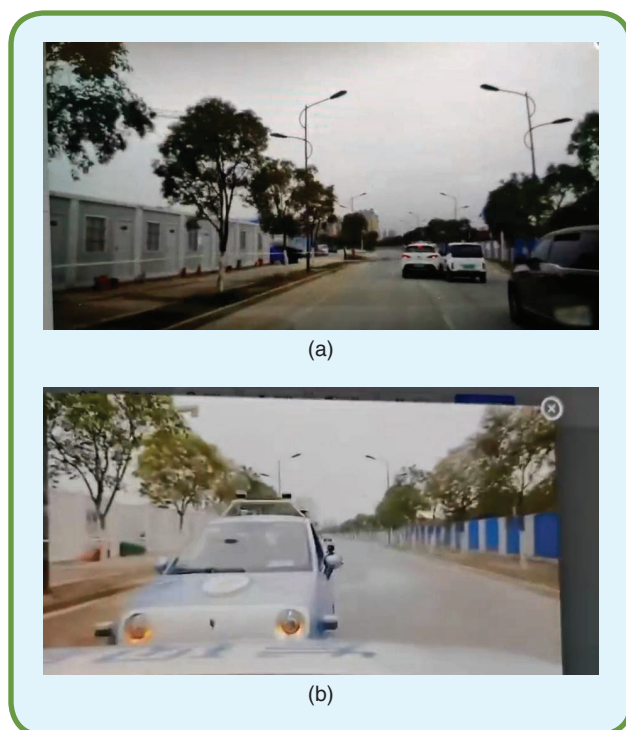

FIG 9 The test tasks for IVFC 2018.

FIG 10 (a) An autonomous vehicle waiting for a pedestrian at IVFC 2017, (b) an autonomous vehicle passing a narrow-down working zone in IVFC 2019, (c) an autonomous vehicle facing the water curtains in IVFC 2019, and (d) an autonomous vehicle entering an underground parking lot in IVFC 2019.

FIG 11 (a) A side collision that occurred during overtaking (recorded by a camera installed on one of the judge vehicles) and (b) a head-on collision that occurred within a conflicting narrow-down road area (recorded by a camera installed on one of the competition vehicles).

FIG 12 The image caught by a camera that monitors the hands of the operator.

port. We also use water curtains to test vehicles' reactions when their visionary sensors are temporarily disabled [as displayed in Figure 10(c)]. It seems that many autonomous vehicle prototypes have not been ready for such extreme working conditions.

The interaction between the testing vehicle and other vehicles has become one focal issue of IVFC. In IVFC 2016–2019, we employed several highly trained instructors from local driving schools in Changshu to drive alongside the challenge vehicles on expressways. Records indicate that most challenge vehicles behave well in a structured road environ-

ment. We also tested the interactions between human-driven vehicles and the challenge vehicles in the testing ground. In IVFC 2009–2019, all of the challenge vehicles were roughly tested, one by one, on the testing grounds. Their departures were appropriately scheduled to minimize interactions. Several collisions between the challenge vehicles and the vehicles driven by the local driving school instructors were recorded. In contrast, in IVFC 2020, we allowed five vehicles at most to simultaneously enter the testing ground so that they could compete for the roads to finish as many simulated riding services as possible. Several collisions among the challenge vehicles were recorded in this test, too. Figure 11(a) displays an accident mainly caused by a wrong movement prediction of another challenge vehicle. Figure 11(b) presents an accident that occurred due to limited sensing capability within a conflicting narrow-down road area forced by an intentionally roadside-parked container truck.

It should be pointed out that IVFCs pay more attention to the sensing and recognition capability of autonomous vehicles since the challenges are guided by the major research plan on "Cognitive Computing of Visual and Auditory Information," supported by the NSFC. Since IVFC 2017, the vehicles have not been required to execute some complex driving actions to pass some areas (e.g., narrow corridors). We expect that future IVFCs will increase the difficulty of decision and action tasks.

The Sensing System and Capabilities

To ensure a fair competition, all of the challenge vehicles are equipped with several kinds of sensors, including the following.

1) They are equipped with looking-in cameras that record the hand and leg movements of the operators. During the last 12 IVFCs, all challenge vehicles were required to keep an emergency mode. This model allows vehicle owners to cancel autonomous driving and immediately stop the vehicle if the vehicles are in danger. Some challenge vehicles used wireless communication to link to the operators while the other vehicles' operators needed to sit in the vehicle. In the early-year IVFCs, some operators of the challenge vehicles slightly steered the wheel or pushed the brake when necessary. This behavior caused great controversy because the judge outside of the challenge vehicle could hardly determine whether the operators had interfered with the vehicles' autonomous driving. Since IVFC 2017, all of the hand and leg movements of the operators have been monitored and recorded with independent cameras (e.g., Figure 12). The unfairness problem was successfully solved.

2) They are equipped with navigation sensors that record the decimeter-level positions of the vehicle per sampling second. Since IVFC 2017, we have used an integrated GPS/INS sensing system that is temporarily mounted onto the challenge vehicles to track their exact positions. This system was found

to work in general. However, sometimes it may malfunction due to considerable interference with the GPS signals. The Radio Regulatory Commission of Changshu was compliant to help eliminate the interference, but we could not explain the interference's cause. Most challenge vehicles are found to be vulnerable to such interference, too.

3) They are equipped with looking-out cameras that record the front-view driving environment and the actions of other traffic participators. The recorded video data has increased our training data set for future autonomous vehicle design and has helped explain the behaviors of the challenge vehicles and the possible causes of their failures.

Moreover, we also used many sensors that are not mounted onto challenge vehicles to monitor the test process (as presented in Figure 13). The road-side cameras are used to check vehicles' behaviors around intersections (e.g., whether a vehicle stops before the stop line). Cameras installed on the unmanned aerial vehicle (UAV) are used to provide a precise and long-term observation of the monitored driving scenarios. Each challenge vehicle is followed by a judge vehicle that is driven by humans. The cameras installed on the judge vehicles monitor some detailed actions of the challenge vehicle. For example, Figure 13(b) illustrates how to determine whether a challenge vehicle wrongly runs across a lane, based on the video data photographed by the camera on the judge vehicle.

All of the data recorded by the road-side cameras are transmitted to the local data center and the cloud data center via optical fiber communication. All of the data recorded by the sensors mounted on the challenging/ judge vehicles and the UAVs are transmitted to the cloud data center via 4G communication in a real-time manner. The data transmission latency has been lower than 1 s most of the time since we have not needed to simultaneously track many vehicles. Since IVFC 2016, each vehicle's information (e.g., position, speed, and ac/deceleration rate) under test has been displayed on the screens in the hall of the local data center (illustrated in Figure 14). It is used to rapidly calculate the performance values of each task. The judges and all autonomous vehicle teams watch this information to guarantee that every competition participant can accept the final scores. In IVFC 2015, when this system was not yet applied, more than 30 officers took more than 12 h after the field test to check the video records of all 25

autonomous vehicles. They took another 3 h to debate with the autonomous vehicle teams about the scores. In IVFC 2016, when this system was first applied, 10 officers

(a)

(b)
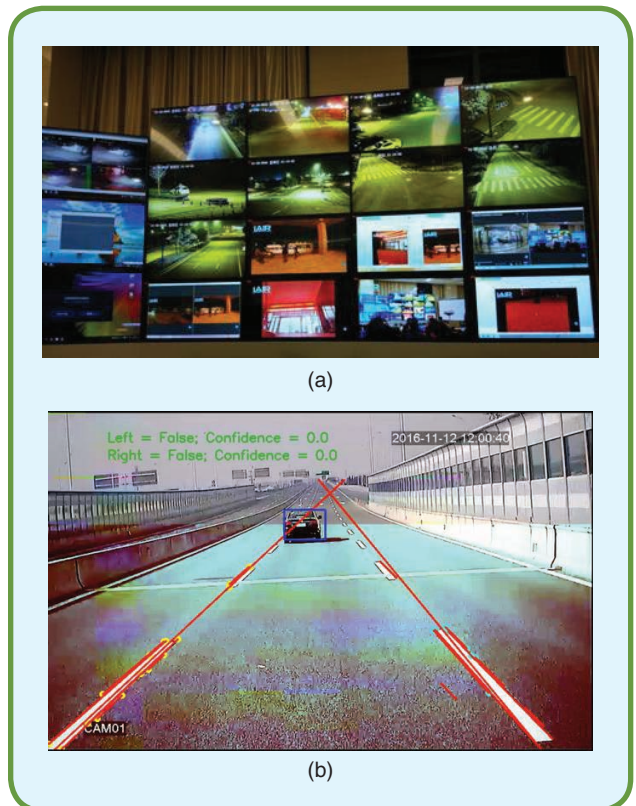
FIG 13 (a) The command-and-monitor center displays the video data collected by the roadside cameras and (b) the video data collected by the camera on the judge vehicle.

FIG 14 The command-and-control center monitors the video data collected by the roadside vehicles, checks them using the camera on the judge vehicle, and displays the real-time positions of the challenging vehicles.

took just 45 min to check the reference scores of all 20 autonomous vehicles and used only 10 min to settle the debate of the final scores, using fast video playback.

Since IVFC 2017, we have also tested possible cooperation between vehicles and infrastructure via V2X communications. In some intersections of our testing grid, the traffic lights have been linked with V2X roadside units. The V2X roadside units wirelessly transmit the status of traffic signals to nearby vehicles so that the autonomous vehicles equipped with V2X-communication onboard units can adjust their vehicle speed and cross the intersection in the most comfortable manner. In IVFC 2018, we also tested the adaptive responsibility of traffic lights. Each approaching vehicle equipped with V2X-communication onboard units will announce its arrival request in advance, and the traffic light that receives this request should switch to green when necessary.

New Theories and Methods for Vehicle Testing

Meanwhile, the objective of IVFC has shifted to establishing a new set of theories and methodologies for the testing of autonomous vehicles. IVFCs are held not only for competition but also for the design of autonomous vehicles that could be used in practice.

Primarily, we would like to highlight a number of issues. First, we need to determine which testing tasks and their associated data are most important to share. Current autonomous vehicle testing is data-centric as the current mainstream machine learning approach is data-driven. Therefore, we have to feed as much data as possible to the models. More than 5 TB of data were recorded in various scenarios during IVFCs and are currently used as an essential source for the future design and testing of autonomous vehicles. Under the support of NSFC, some of these data have been published by academic institutions as research benchmarks since 2017. Based on user feedback, we found that there is a need for an open, scenario-based, conceptually oriented, and widely accepted testing data-exchange format. Noticing that every autonomous vehicle company has generated massive field-test or simulation-test data, we find that other institutions or companies' video or GPS data have become less important and hard to re-use (noticing that the sensors on different autonomous vehicles are usually different in various metrics). We find it is more useful to share the problematic scenarios identified in testing because they may also be challenges for other autonomous vehicle prototypes.

Second, testing autonomous vehicles is complex and should be finished mostly automatically under human experts' guidance and monitoring. Human experts are still heavily involved in the description and design of test tasks because of the experience and intuition they have gained through finishing those tasks themselves. Human experts have gradually been relieved from the tedious, time-consuming, and error-prone test task-evaluation process. In 2017, the integrated IVFC testing system formulated a closed loop for data collection, task evaluation, and new task generation (presented in Figure 15). Using the concept of parallel driving and the method of parallel testing, this system not only reduces evaluation errors but also accelerates the whole testing process [12], [13].

Third, researchers are now focusing on finding new tasks that will be challenging for the vehicles and on how to guarantee that we have tested all possible challenging tasks. Parallel learning that combines both field tests and simulation-based tests might be the answer to these problems. IVFC picks up the tasks that human experts thought were complicated and the ones that were difficult in virtual tests in the virtual, parallel world [14]–[17]. To save time and money, simulation tests will be carried out before field tests to determine whether a scenario is worth examining. Specifically, a technique called *parallel vision* was proposed in [14] to quickly generate simulated, visual sensing data that are as real as possible from the testing vehicles. Moreover, the search for new challenging tasks and the evaluation of tasks should be formulated within a closed, self-boosting loop, which is called *parallel learning* [16], [17]. The task-generation subsystem will self-update based on the scores from the passed tasks and will seek new challenging tasks because testing obsolete and ordinary scenarios is usually meaningless. Some explanations for this theory can be found in [11].

Preliminary Conclusions and Perspectives

IVFC serves as a manifesto, as propaganda, and, simultaneously, as a seeding machine to Chinese autonomous vehicle research. Before the first IVFC in 2009, few people in China paid attention to this emerging research topic. After 12 years, IVFC has successfully triggered many students' research enthusiasm; and most of these students have either established or joined the compromising innovative companies of autonomous vehicles in China [18].

The tests in IVFCs have indicated that urban environments may still be challenging for current autonomous vehicles since the driving environment is not always well-structured and the autonomous vehicles need to operate among other vehicles. The behaviors of other traffic participators are not always easy to predict in urban environments. How to operate well with other vehicles (either human-driven or autonomous) is a question that is yet to be thoroughly answered. Some challenge vehicles have followed defensive driving strategies, which has led to sluggish operations. Others have followed competitive driving strategies, which has led to collisions with other vehicles during the tests. We have found that different autonomous vehicle designers should follow negotiation (without wireless communication support) or cooperation principles (with wireless communication support) [19], [20].

The test results of IVFCs show that the limits of current sensors and decision algorithms could be overreached in some scenarios. Clearly, at this moment, autonomous vehicles are still vulnerable to various disturbances and attacks
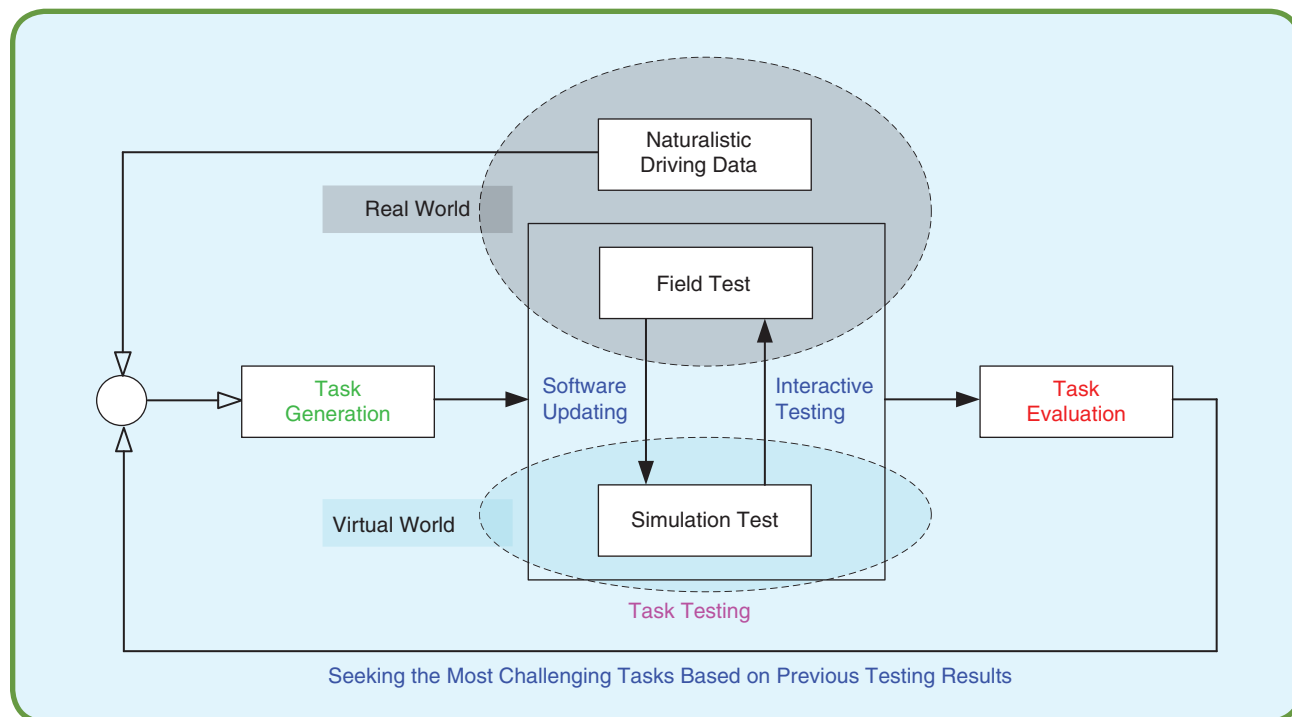
FIG 15 The task flow of the integrated IVFC test system

(e.g., extreme lighting conditions, rain or storms, and malicious GPS interferences). It may take great efforts to find the solutions to deal with such disturbances and attacks.

IVFC will continue to be held in China to encourage more people to participate in the design and test of autonomous vehicles. New proving grounds will also be constructed, and more testing data will be made publicly accessible [21]. We hope most autonomous vehicles will be able to pass all of the tasks that we will imagine and design for IVFC 2030.

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