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Advanced Test Tools for ADAS and ADS

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16. Abstract

This document describes the current test tools and capabilities established at NHTSA’s Vehicle Research and Test Center (VRTC) for researching the safety performance of advanced driver assistance systems (ADAS) and automated driving systems (ADS) in a closed-course setting. This paper focuses on immediate and future needs for ADAS and ADS closed-course testing and the requirements for basic operation, coordination, and a scalable system that can perform repeatable and reproducible tests that require precise control of multiple actors in a realistic driving scenario of relevance to the system of interest.

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1. Introduction

This report describes current test tools the National Highway Traffic Safety Administration's (NHTSA) Vehicle Safety Research (VSR) Office acquired and developed to research the safety performance of advanced driver assistance systems (ADAS) and automated driving systems (ADS) in a closed-test-track environment. Particularly, this report focuses on those tools that enable coordination and precise control of other actors around a vehicle that is equipped with an ADAS or ADS such that the subject system of interest can be placed in a conflict scenario to observe its behavior. VRTC's progress and approach for developing the current test tools is discussed, followed by a discussion of current hardware being used and testing capabilities. Collectively, these tools enable repeatable and reproducible test choreography of surrounding actors in a complex, multi-actor test scenario.

1.1 Purpose

The goal of advanced test tool development is to support performance-based testing in a closed-course test-track setting. Leveraging knowledge and tools from past ADAS research, the development of new test tools expands the use of surrogate and real vehicles that can be remotely controlled to orchestrate multi-actor scenarios.

1.2 Overview

This paper is structured as follows: Section 1.3 provides a brief introduction to VRTC's history in evaluating vehicle safety systems on a closed course. Section 1.4 discusses objectives and requirements for VRTC's current track testing needs. Section 2 provides a detailed explanation of current hardware and tools developed to address testing requirements, along with data collection systems associated with these testing systems. Section 3 explains the development and execution of test scenarios. The paper concludes with a summary of the current systems in Section 4.

1.3 Background

VRTC has a long history of evaluating vehicle safety systems on a closed course. This history began in the 1990s with un-tripped rollover research and continued from 2000 to 2010 with electronic stability control research and the research of some of the first ADAS technologies such as blind spot detection, forward collision warning, and lane departure warning. It was the introduction of these advanced safety features that motivated the agency to start using more advanced test tools to enable repeatable, reproducible, and technology-neutral test methods. Test tools used in early development by the agency to evaluate these advanced safety features included steering, brake, and accelerator robots, along with surrogate vehicles that appear realistic and could be struck from a rear approach angle. These older types of surrogate vehicles were typically towed by a support vehicle.

The next set of vehicle safety systems, which emerged in the 2010–2016 timeframe, included rearview video systems, automatic emergency braking, pedestrian automatic emergency braking, rear automatic emergency braking, rear cross traffic alert, and lane keeping support. These systems continued to add to the array of ADAS technologies available in production vehicles.

These vehicle system advancements required improvements to current testing equipment to enable safety evaluation and test procedure development activities of these ADAS technologies. This was done by improving steering, brake, and accelerator robots' hardware and software for more accurate closed loop vehicle control and improving surrogate vehicles, including the addition of surrogate pedestrians, cyclists, and vehicles that appear realistic and could be struck from any approach angle. Low-profile robotic vehicles for moving targets and ground-based pullers for moving "pedestrians" replaced previous methods to move surrogate targets, such as by towing targets behind support vehicles.

The current set of advanced vehicle technologies included in agency testing efforts (2016 to present), includes both ADAS and ADS systems. For ADAS, this mainly consists of emerging active safety systems (defined as Level 0 driving automation system per SAE J3016) as well as Level 1 and Level 2 driving automation systems. For Level 0 active safety systems, these technologies include intersection safety assist, opposing traffic safety assist, and blind spot intervention. Level 1 driving automation systems being tested include lane centering control[1] (when not used in conjunction with any other longitudinal control system such as adaptive cruise control). Level 2 driving automation systems being tested include highway driving assist and traffic jam assist. In addition, vehicles equipped with ADS which is a subset of the broader driving automation category are starting to emerge (defined as Levels 3-5 per SAE J3016). Examples of emerging ADS-equipped vehicles include low speed passenger shuttles and delivery vehicles. Collectively, these new driving automation and active safety systems have driven the need for new testing capabilities at VRTC. In order to have the opportunity to evaluate these vehicle technologies in a closed-course setting, further improvements in test equipment and tools are required so that scenarios representative of situations within these systems' operational design domain (ODD) can be replicated. These technologies introduce the potential for new logistic challenges imposed by geofencing, such as requiring the closed-course facilities to be mapped and be within the ODD of the vehicle to be able to perform the traditional closed-course testing to achieve repeatable and reproducible results. These advanced vehicle technologies also add the complexity of multi-actor scenarios that require coordination and communication between vehicles and surrogate targets while still maintaining the highest level of safety for anyone involved in conducting these tests. An overview of these requirements and objectives for testing is presented in Section 1.4.

1.4 Objectives and Requirements

Given the current state of vehicle safety systems and the development of new emerging ADAS and ADS technologies, a list of requirements and objectives for an advanced testing system enabling closed-course multi-actor testing capabilities was developed.

The first step in identifying requirements and objectives was a literature review of scenarios and crashes that emerging ADAS and ADS systems might encounter. A list of test maneuvers from these scenarios was compiled referencing Pre-Crash Scenario Typologies for Crash Avoidance Research (Najm et al., 2007), V2V pre-crash scenarios (Najm et al., 2013), California PATH behavioral competencies (Nowakowski et al., 2014), and the Federal Automated Vehicle Policy behavioral competencies (U.S. Department of Transportation, 2016). Per Najm et al. (2007), a vehicle maneuver denotes passing, parking, turning, changing lanes, merging, and successful

[1] Also sometimes known as lane-keeping assist, lane-centering assist, lane-keeping support, etc.

corrective action to a previous critical event. A table of these maneuvers for each reference can be found in the appendix. From these maneuvers and behavioral competencies, only those that contain other actors such as vehicles, pedestrians, cyclists, or animals were considered for the context of this report. For example, the pre-crash scenarios dealing with vehicle failure and control loss (Najm et al., 2007) do not require any additional actors or test tools, so they were not addressed since they could already be tested with existing tools.

From this condensed set of maneuvers that contain other actors, further analysis was performed to determine the number of vehicles and vulnerable road users (VRU) (pedestrians, bicyclists, animals, etc.) that would be needed to perform the given maneuver. The actors were further classified based on whether they were at risk of a collision in the scenario, in which case the role of the actor in the scenario would need to be performed by a surrogate strikeable actor. Also, actors were classified on whether they needed to be moving or static for a given maneuver. A list of maneuvers that were selected and the number and type of actors needed for each maneuver is shown in Table 1. For each actor type, short hand notations were used for conciseness with pedestrians being denoted by the letter p, bicyclist with the letter b, animal with the letter a, and vehicle with the letter v.

Table 1. Test Maneuvers and Required Actors

No.	Scenario	# Strikeable			# Non-Strikeable	Total Actors
		Moving		Static	Moving	
		Vehicles	VRUs (p/b/a)	Actors (p/b/a/v)	Vehicles	
1	Respond to speed limit change and speed advisory	0	0	0	1	1
2	Perform high/low-speed merge	1	0	v	1	3
3	Move out of travel lane and park	1	0	2v	0	3
4	Respond to encroaching oncoming vehicle	2	0	2v	2	6
5	Detect passing and no passing zones and perform passing	1	0	v	2	4
6	Perform car following (including stop and go)	1	0	0	0	1
7	Respond to stopping vehicle	1	0	0	3	4
8	Respond to lane changes	2	0	0	2	4
9	Respond to static obstacle in path	1	0	v	0	2
10	Navigate intersections and perform turns	2	0	2v+	2	6
11	Navigate roundabouts	0	0	v	2	3
12	Navigate a parking lot and locate spaces	1	0	2v+	1	4
13	Respond to work zones and person directed traffic	0	0	p	4	5

No.	Scenario	# Strikeable			# Non-Strikeable	Total Actors
		Moving		Static	Moving	
		Vehicles	VRUs (p/b/a)	Actors (p/b/a/v)	Vehicles	
14	Respond to access restrictions	1	0	v	0	2
15	Make appropriate right-of-way decisions	2	0	3v	2	7
16	Respond to emergency vehicles & bus	0	0	v	4	5
17	Yield and provide safe distance for pedestrians and bikes	0	p+b	2v+p+b	1	7
18	Animal crash avoidance	0	a	0	1+	2
19	Back out of urban area	0	0	2v+p	1	4
20	Respond to encroaching vehicle same direction	1	0	0	3	4
	Resources Required (Max)	**2**	**p+b+a**	**p+b+2v+**	**4**	**7**

To cover most of the maneuvers presented in Table 1, two moving surrogate strikeable vehicles, four moving non-strikeable (real) vehicles, and one surrogate strikeable pedestrian, bicyclist, and/or animal target are required. Currently, no surrogate strikeable animals are being used in VRTC's testing.

In addition to the number of required actors, additional test system requirements and objectives to perform the maneuvers include the following:

- Maintain the highest level of safety for anyone involved in conducting the test.
- Coordinate and communicate between actors.
- Generate and conduct the complex choreography required by the scenarios.
- Simulate and verify that the maneuver is feasible before testing.
- Efficiently conduct testing.
- Accurately collect and synchronize data generated during testing.
- Error reporting capability.
- Maintain repeatability and reproducibility.

How these requirements and objectives are addressed by VRTC's advanced test system are detailed in Section 2.

2. VRTC's Test Tools

Based on the requirements presented, VRTC's advanced test system consists of two moving strikeable surrogate vehicles, four robotically controlled non-strikeable vehicles, and a pedestrian/bicyclist apparatus. These actors can all be integrated into a test by using software to enable closed loop control between all actors relative to the independently acting ADAS or ADS system under test. This ensures accurate, repeatable, reproducible test results. Each type of actor is further explained in this section, but first some additional test scenario definitions are introduced for consistency with test procedures and clarity in scenario descriptions.

In describing a scenario, the subject vehicle (SV) is the actor of interest for the given test. This can also be referred to as the subject under test (SUT). To clarify, the ADAS/ADS of the SV that is being tested is not under direct control during the actual test, rather it can respond to the scenario that is presented to it. Typically, a test scenario will have one other actor that is the main antagonist for the test, defined as the principal other vehicle (POV). Significant other vehicles (SOV) are other actors that complement the POV and enable the test to be performed as desired. For example, from NHTSA's traffic jam assist draft research test procedure (NHTSA, 2019), the suddenly revealed stopped vehicle scenario shown in Figure 1 includes a strikeable POV as the revealed vehicle and the non-strikeable SOV as the vehicle revealing the stationary POV.

When choosing the type of vehicle used in the test scenario, non-strikeable, production vehicles are often preferred because they provide the most inherently realistic appearance to the SV sensing system. However, during scenario development, each POV/SOV path is mapped and reviewed for possible collisions with other actors. If there is a risk of collision, a strikeable surrogate is used in lieu of an actual vehicle to avoid danger to personnel and equipment involved in testing.

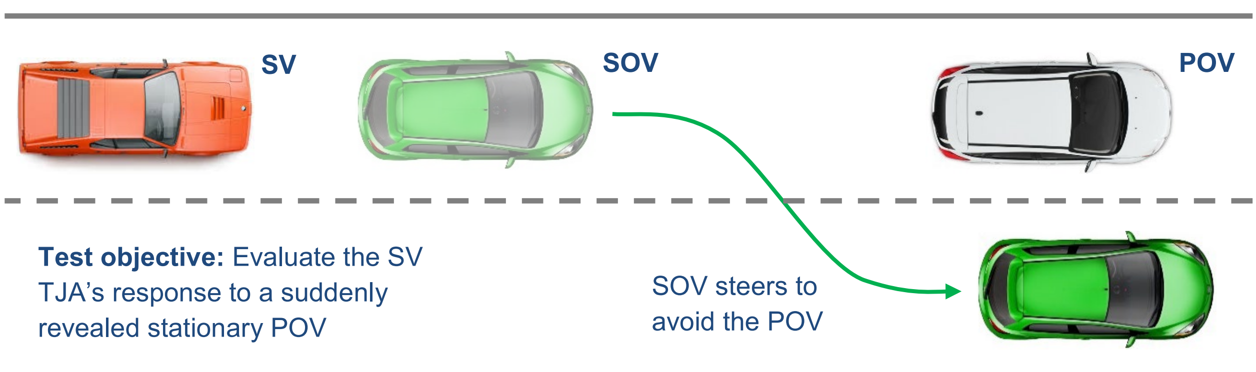

Figure 1. Suddenly Revealed Stopped Vehicle Scenario

2.1 Non-Strikeable Vehicles

Non-strikeable vehicles are standard production cars. Typically, the SV and SOV are non-strikeable vehicles and the POV is a strikeable vehicle. These non-strikeable vehicles can be manually controlled or robotically controlled. Manual control means a human driver controls the vehicle's lateral and longitudinal position. The benefit of this type of vehicle control is ease of use and set-up time. However, with the increased constraints and complexity in test scenarios, a robotically controlled vehicle provides higher accuracy and repeatability but at the cost of increased complexity. The two methods of robotically controlling non-strikeable vehicles are detailed below.

2.1.1 Robotic Drop-in Kits

The first method used to robotically control a non-strikeable vehicle is a robotic "drop-in" kit comprised of actuators attached to the steering wheel, accelerator pedal, and brake pedal. Robotic drop-in kits are not a conceptually new technology, but their size, weight, and functionality have improved when compared to the earlier iterations. ADAS test procedure development relies on this technology to produce repeatable and reproducible steering, accelerator, and brake inputs for the POV and SOVs in the test. These robot kits can work independently or as a system and can be used to control the steering, acceleration, or braking or any combination of the three.

There are multiple options available to meet the requirements mentioned above, however the robotic drop-in kits used in VRTC's advanced test system are produced by AB Dynamics (ABD)[2] and are used in conjunction with equipment from Oxford Technical Solutions.[3] Each are briefly described below.

2.1.1.1 AB Dynamics Steering SR15 Orbit Robot

An ABD SR15 Orbit steering robot can accurately and repeatedly perform path following and be programed for abort maneuvers.[4] The SR15 Orbit is a lightweight, low torque module, that mounts directly to the steering wheel without the need to remove the airbag as shown in Figure 2. It can be programmed to release steering control to allow the SV to respond to inputs by the ADAS/ADS and then to regain control of the SV to prevent loss of control or unintended collisions.

2.1.1.2 AB Dynamics Combined Brake and Accelerator Robot

An ABD combined brake and accelerator robot (CBAR) can accurately and repeatedly perform longitudinal control within any given scenario's velocity requirements with precise brake and accelerator inputs. [5] The CBAR still allows a human driver to operate the vehicle from the driver's seat, even with the robots installed as shown in Figure 2. The driver is always able to override the steering, brake, and/or accelerator robots and take control of the vehicle if necessary.

2.1.1.3 Oxford Technical Solutions RT 3002 and Range S

Oxford Technologies RT 3000 series units have integrated inertial measurement units (IMUs) and GPS with differential corrections that combined provide high accuracy (1 centimeter)

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[2] Anthony Best Dynamics Limited, Wiltshire, England.
[3] Oxford Technical Solutions Ltd., Oxfordshire, United Kingdom, often abbreviated OxTS.
[4] www.abdynamics.com/en/products/track-testing/driving-robots/steering-robots.
[5] www.abdynamics.com/en/products/track-testing/driving-robots/pedal-robots.

position data.[6] Paired with an Oxford Technologies Range S system, relative ranges and velocities between all actors and surveyed lane markings or points can be collected.[7]

Figure 2 shows a Ford Fusion that has been instrumented with steering, brake, and accelerator robots. Mounted on the roof are antennas for GPS, GPS corrections, and a wireless network for system communications. Mounted in the trunk is the main controller, power pack, and GPS/IMU. As previously mentioned, installing steering and pedal robots still allows space for the driver to occupy the seat and monitor the system. The driver can overtake the system if necessary and operate the vehicle.

[6] www.oxts.com/products/rt3000/.
[7] www.oxts.com/products/rt-range-s/.

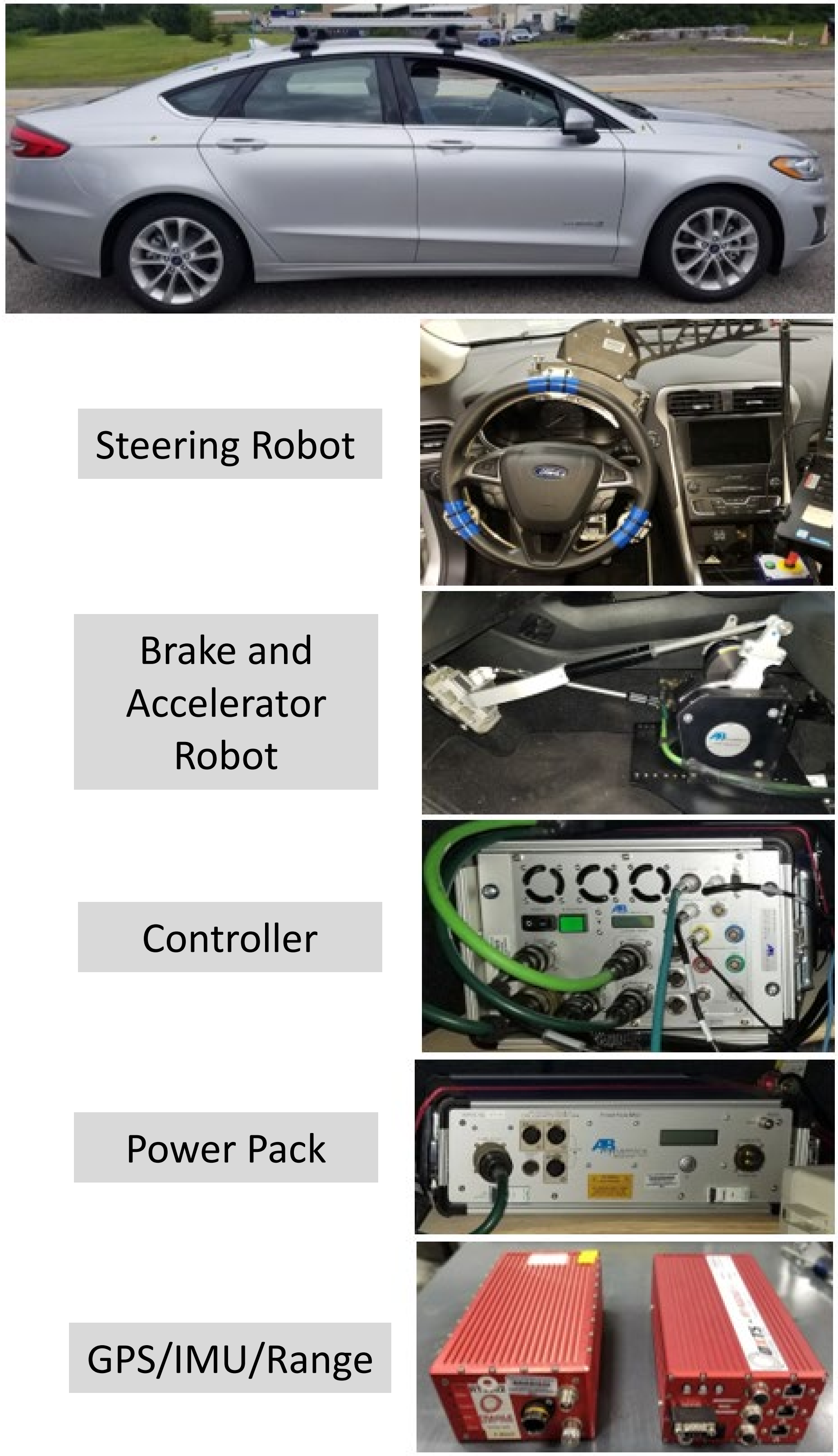


Figure 2. Non-Strikeable Vehicle With Robotic Drop-in Kit Components

2.1.2 Drive-by-Wire

Another method for robotically controlling a non-strikeable vehicle is using a drive-by-wire kit. This method uses the actuators already installed in the factory vehicle. The drive-by-wire system uses an interface to these actuators to send steering, accelerator, and brake commands either manually with a joystick or controller or programmatically. The benefit of this type of robotic control is that no additional actuators need to be mounted in the vehicle which allows for greater driver comfort and reduced cost. However, this method has a few limitations. Most OEM installed actuators have limited capabilities in terms of torque for steering input and stroke rate for accelerator and brake inputs. Another limitation of drive-by-wire kits is the reliance on a vehicle control interface for communication with these actuators. A few retrofit kits are available for certain vehicles, but not all vehicles have the necessary factory installed actuators and vehicle interface. Typically, a retrofit kit taps into the vehicle's controller area network (CAN) bus and send control signals to the vehicle actuator. Figure 3 shows a Lincoln MKZ instrumented with a DataSpeed retrofit kit by AutonomuStuff that interfaces with the vehicle systems for controlling the steering, brake, and accelerator of the vehicle.[8] This vehicle has factory default drive-by-wire for controlling all three systems. In addition to the drive-by wire capabilities, other sensors were added to the vehicle for data collection and to enable a research platform for higher levels of automation.

[8] https://autonomoustuff.com/product/adas-kit/.

Figure 3. Non-Strikeable Vehicle With Drive-by-Wire Components

2.2 Strikeable Surrogate Actors

In scenarios where an actor has a high risk of being in a collision, a strikeable surrogate actor is used. For pedestrians, regardless of the scenario, a strikeable surrogate pedestrian is used to eliminate any safety concerns of incorporating a real pedestrian into a testing scenario. The following sections will discuss the surrogate vehicle and surrogate pedestrian/bicyclist used in VRTC's advanced test system.

2.2.1 Guided Soft Target

As defined in NHTSA's draft traffic jam assist draft research test procedure (NHTSA, 2019), an appropriate surrogate vehicle must possess the following attributes:

A. Accurate physical characteristics (e.g., visual, dimensional) when viewed from any approach angle.

   I. Body panels and rear bumper shall be white in color.

   II. Simulated body panel gaps shall be present.

   III. The simulated rear glass and tires shall be dark gray or black.

   IV. A rear mounted, United States-specification license plate, or reflective simulation thereof, shall be installed.

B. Reflective properties representative of a high-volume passenger car when viewed from any approach angle by radar (24 GHz and 76-77 GHz bands) and lidar-based sensors.

C. Remains consistently shaped (e.g., visually, dimensionally, internally, and from a radar sensing perspective) within each test series.

D. Resistant to damage resulting from repeated SV-to-POV impacts.

E. Inflicts minimal to no damage to the SV, even in the event of multiple impacts.

The strikeable surrogate vehicle used in VRTC's advanced test system is called the global vehicle target (GVT). The GVT has characteristics of a compact passenger car and consists of foam panels and skins that are designed to separate upon impact, as shown in Figure 20. The GVT is designed to appear realistic to the radar, camera, and lidar sensors used by automotive safety systems and automated vehicles (Euro NCAP Secretariat, 2018).

Appropriate radar characteristics are achieved by using a combination of radar reflective and radar absorbing material within the GVT's vinyl covers. Internally, the GVT consists of a vinyl-covered foam structure.

The GVT is combined with a low-profile robotic vehicle (LPRV). The GVT and LPRV are shown in in Figure 4. The LPRV is programmable and allows the GVT's movement to be accurately choreographed (5 cm path following accuracy) and repeated by using IMU/GPS data and communication networks to perform closed-loop control. The LPRV's design allows the SV to drive over it. The GVT is secured to the top of the LPRV robotic platform using Velcro attachment points. The GVT and LPRV together are referred to as the guided soft target (GST).

Multiple fail-safe measures are designed to ensure the safe operation of the GST. If a test vehicle impacts the GVT at low speed, the GVT is typically pushed off and away from the LPRV and the LPRV is pushed against the ground and stops as the test vehicle is driven over it. At higher impact speeds, the GVT breaks apart as the SV essentially drives through it. The GST can be repeatedly struck from any approach angle without harm to those performing the tests or the vehicles being evaluated. The GST can be operated at speeds up to 80 kmh and sustain impacts at relative velocities up to 110 kmh. Reassembly of the GVT occurs on top of the LPRV and takes a team of 3 to 5 people approximately 7 to 10 minutes to complete. Extensive collaborative research was performed from 2015 to 2018 to significantly improve how realistic the GST system appeared to the systems designed to respond to real vehicles (Snyder et al., 2019). The GST system provides accurate closed-loop control of the POV relative to the SV, and because it is strikeable from any approach aspect it can be incorporated into nearly any pre-crash scenario.

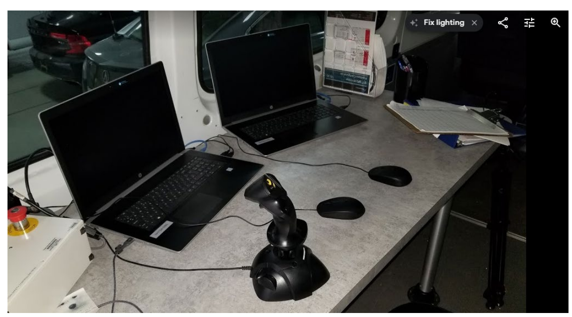
2.2.1.1 Support Vehicle

To operate the GST, a support vehicle is needed to provide good visibility to observe the test, the necessary controls to execute the test, and a safety controller to abort the test if necessary. An example of this is shown in Figure 5.

Figure 4. LPRV GPS Guided Platform With GVT

Visibility

Scenario Monitor



Safety Controller

Figure 5. VRTC's Advanced Test System Support Vehicle

2.2.2 Strikeable Surrogate Pedestrians

The strikeable surrogate pedestrians used in VRTC's advanced test system are the 4ActiveSystems (4a) pedestrian static (4activePS) and pedestrian articulated (4activePA) mannequins.[9] [10] The static mannequins, referred to as poseable, have arms and legs that can be manually positioned pre-test but do not actively articulate during test conduct. The articulated mannequins have actively articulating legs and poseable arms. VRTC has both static and articulated adult- and child-sized mannequins. Each of these mannequins have radar, visual, and near infrared characteristics representative of their actual (human) equivalents and can be struck at speeds up to 60 kmh (37.7 mph).[11]

2.2.2.1 4a Adult and Child Poseable Mannequins

The 4a poseable mannequins consist of an inner foam core and a one-piece cloth cover. The arms can rotate at the shoulders through a limited range of motion, the positioning of the arms is set by the experimenter before running a test. The spacing of the legs is determined by the positioning of the mannequins on the platform. The mannequins have metal pucks on the bottom of the feet that are held in place by magnets in the platform. The adult mannequin also has a separate support pole that is attached by a strap around the waist, the pole provides additional stability. The 4a poseable mannequins can be seen in Figure 6.

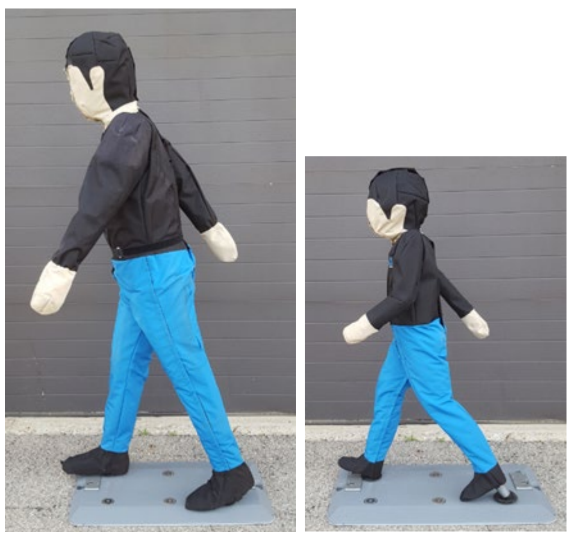


Figure 6. 4activePS Adult (left) and Child (right) Poseable Mannequins

[9] www.4activesystems.at/en/products/dummies/4activeps.html.
[10] www.4activesystems.at/en/products/dummies/4activepa.html.
[11] https://cdn.euroncap.com/media/43371/euro-ncap-aeb-vru-test-protocol-v301.pdf.

2.2.2.2 4a Adult and Child Articulated Mannequins

The 4a articulated mannequins consist of inner foam core and cloth covers for the torso, arms, and legs. Attached to the torso is a pole that interfaces to the platform for stability. The poseable arms can rotate at the shoulders through a limited range of motion, the positioning of the arms is set by the experimenter before running a test.

The legs of the articulated mannequins are configured to actively articulate during testing. Each leg is a self-contained piece separate from the main body. The construction of the legs is the same as the torso, consisting of a foam core and outer cover. The articulation is achieved using servos attached to the mannequin's support pole, and the legs are attached to the servos via magnets. Additionally, the adult mannequin has a passive (non-powered) knee joint.

These mannequins have a pre-set articulation profile that represent an adult or child movement speed (walk/run). A hand-held controller is used to select the desired articulation profile as well as start and stop of the articulation. The mannequins have a control function that moves the servos to a pre-programmed position when armed. This assures that the articulating motion of the limbs starts from the same position for every test and, therefore, presents the mannequin in a more consistent and repeatable manor. The 4a adult and child articulated mannequins can be seen in Figure 7.

Figure 7. 4activePA Adult (left) and Child (right) Articulated Mannequins

2.2.2.3 4activeBS Static Bicyclist

In additional to the adult and child mannequins, VRTC's advanced test system also uses the 4a static bicyclist (4activeBS) to represent a bicyclist in a test scenario as shown in Figure 8. The 4activeBS has rotating wheels for realistic characteristics. The dummy is built upon a modular system and spare parts are easy to change. The torso of the dummy is adjustable to different angles, from a "sporty" bent-over position to an upright position. Another option for the 4activeBS are movable pedals and additional reflectors. The 4activeBS can be struck at speeds up to 60 kmh (37.7 mph) for crossing scenarios and 45 kmh (27.96 mph) for longitudinal scenarios.

Figure 8.4activeBS Static Bicyclist

2.2.2.4 ABD Soft Pedestrian Target System

The ABD soft pedestrian target (SPT) system is used to perform testing using the pedestrian mannequin or bicyclist.[12] [13] ABD's SPT system uses a flat belt propulsion system to move the mannequin or bicyclist along the test course. The propulsion system is powered by a steering robot which is controlled using ABD's software. ABD's SPT flat belt propulsion system consists of a ground based SPT20 drive unit that is powered by a steering robot. A SR60 steering robot mounts directly to the drive unit, as shown in Figure 9. The SPT20 is held in place using four blocks weighing 44 pounds each.

[12] www.abdynamics.com/en/products/track-testing/adas-targets/soft-pedestrian-target.
[13] www.abdynamics.com/en/products/track-testing/adas-targets/synchro.

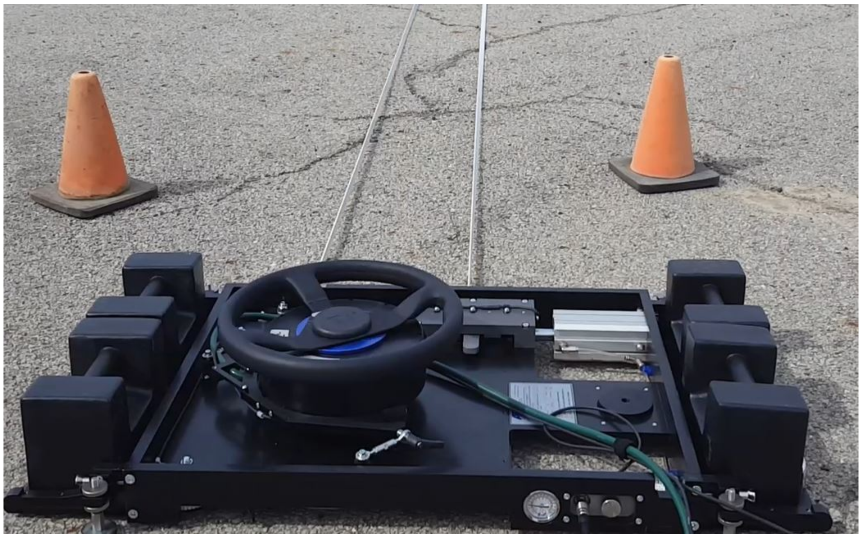


Figure 9. SPT20 Drive Unit With SR60 Steering Robot

The steering robot is connected to control unit consisting of a power supply, controller, and a laptop with ABD’s software. The control unit was housed in a nearby support vehicle. The support vehicle setup can be seen in Figure 10.

Figure 10. Support Vehicle With Steering Robot Controller and Laptop

The drive belt is fed through the underside of the SPT20 drive unit and guided along the test course using a weighted pulley arrangement. The pulley arrangement consists of a return pulley and an optional corner pulley. The corner pulley can be used to guide the belt through a 45° or 90° angle. The pulleys are anchored in place on the test course using interlocking plates as ballast. Each plate weighs approximately 44 pounds (20 kg). The pulleys and weights can be seen in Figure 11.

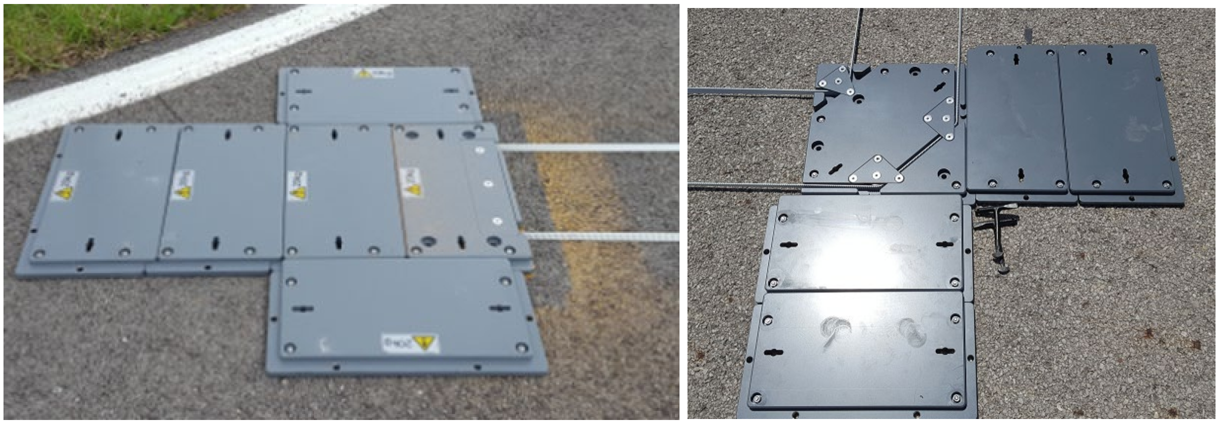


Figure 11. Pulleys and Anchoring Weights

Both ends of the belt attach to a platform via cam lock attachments. The design of the attachment points allows the belt to release from the platform under impact and be quickly reattached. The platform is the component within the SPT system on which the mannequins are mounted. The platform is embedded with an arrangement of magnets that act as mounting points for the poseable mannequins. An additional interface can be attached to the platform for supporting the pole of the articulating mannequins. The platform, with belt attached, can be seen in Figure 12. The system can pull a 15-kg payload at speeds up to 20 kmh in a straight line along the belt path.

Figure 12. Platform With Belt Attached

2.3 Data Collection Systems

All sensors and equipment in the actors (vehicles, pedestrians, etc.) in VRTC's advanced test system generate significant amounts of data. This data needs to be captured and synchronized so that the scenarios and SV performance can be analyzed and evaluated. Currently, two data acquisition systems are used to capture and synchronize data. Common hardware in terms of power, I/O, communication, and even computers are shared amongst systems to allow flexibility and modularity. Each system is similar in its capability of recording CAN data, analog and digital inputs, and video. However, user interfaces and differences in capabilities described below allow engineers to select a system that best suits their needs.

2.3.1 Video CAN Data Acquisition System

Video CAN Data Acquisition System (VCDAS) is an in-house developed system used for video and data collection. This is a stable system customized to VRTCs core track testing needs. The VCDAS hardware can be seen in Figure 13.

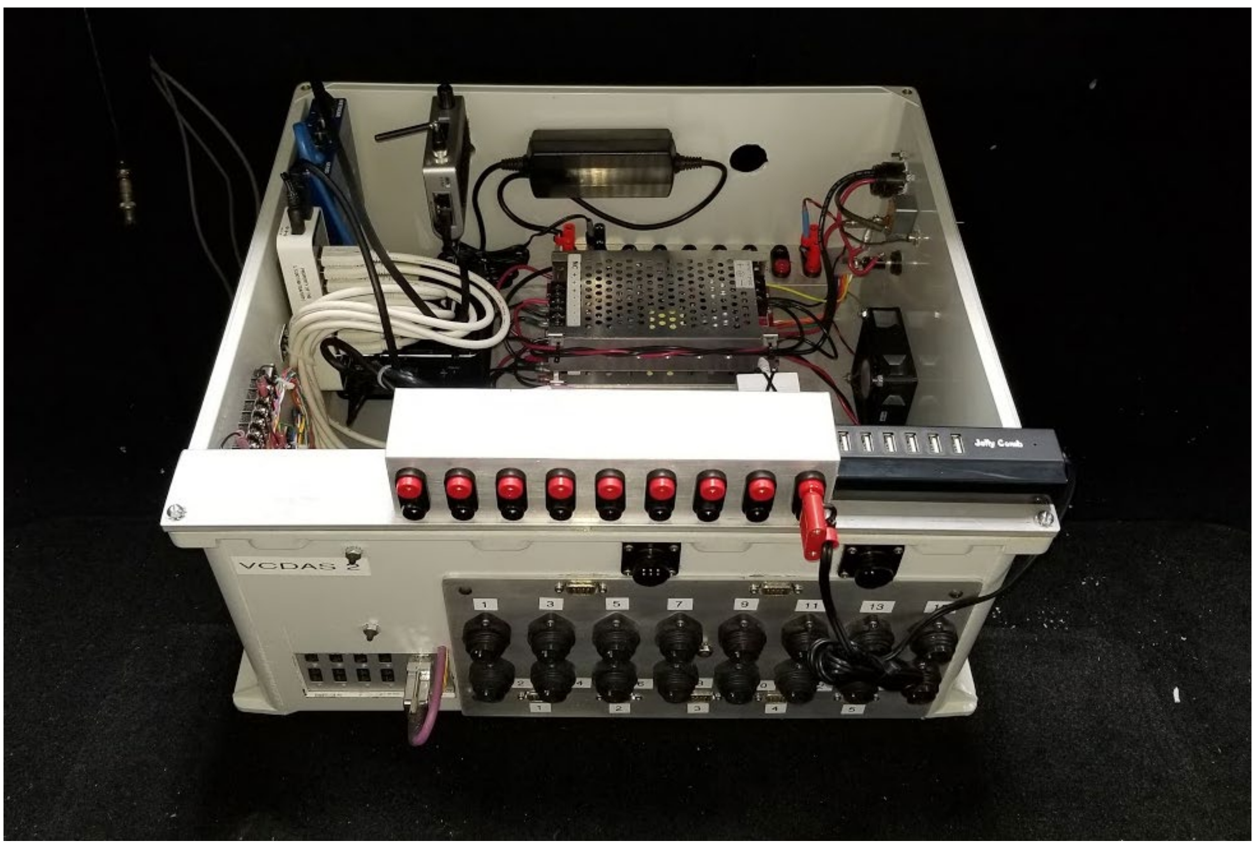


Figure 13. Video CAN Data Acquisition System

The basic VCDAS configuration has 8 CAN ports, of which 7 are available for input. The eighth port is dedicated for onboard digital, analog, or thermocouple inputs. VCDAS also has the built-in capability to monitor and control multiple GoPro cameras using hardware developed by

Timecode Systems.[14] Timecode SyncBacPro and Pulse components, shown in Figure 14, are used to embed time code directly into a GoPro camera file and to remotely monitor and control the cameras.

Figure 14. Timecode Systems SyncBacPro and Pulse Hardware

2.3.2 Robot Operating System Data Acquisition System

This system uses the open source robot operating system (ROS)[15] software for data collection and synchronization. It uses similar hardware to the VCDAS, as shown in Figure 15, and primarily takes CAN signals as inputs, along with network IP cameras. Benefits include externally maintained software, on-going updates, and community support.

[14] Timecode Systems, Worcester, United Kingdom, www.timecodesystems.com/.
[15] Original authors: Willow Garage, Menlo Park, California; Stanford Artificial Intelligence Laboratory; Open Robotics, Mountain View, California.

Figure 15. Robot Operating System Data Acquisition System

2.4 Positioning Data for Closed-Course Scenarios

Performing most test scenarios requires knowledge about the precise position of each actor. To realize this, a majority of VRTC's advanced test tools use GPS measurements combined with data collected from IMUs. A local base station is used to provide real-time kinematic (RTK) corrections to each GPS-based measurement and provides 1-centimeter relative accuracy amongst actors. The base station consists of a GPS receiver, the actual GPS base station computer and hardware, and another radio antenna to communicate the RTK corrections with the actors. VRTC currently maintains 2 GPS base stations shown in Figure 16.

Figure 16. GPS Base Stations

3. Developing and Executing Closed-Course Scenarios

VRTC uses a software package from ABD, called Synchro, to use the hardware described in Section 2 in executing closed-course scenarios. The typical scenario development process is as follows:

1) Design actor paths based on the test procedure using ABD's simulation software.
    a. Test procedure contains tolerances and validity constraints based on equipment capability and empirical evidence.
2) Add maneuvers for each actor on top of the path.
    a. Maneuvers consist of triggers, desired velocities/accelerations, and operation type (closed loop, target point, release to open loop, etc.).
3) Define boundaries for safety.
    a. Boundaries are drawn on top of a map to define areas where the vehicle should not enter.
4) Confirm scenario choreography with slow speed test.
5) Execute test.
6) Analyze results.

The first step in developing a test scenario requires developing a path for all the actors. Paths are a series of XY coordinates locally referenced to the test site. On top of each of the actor's path, the desired maneuvers are added in terms of speed, relative position, open-loop control, collision timing, etc. All actors navigate by comparing GPS position (converted to local coordinates) and path coordinates. The error between the desired path and relative distances and the current state is calculated and converted to control signals that adjust the actor's position to stay on path and achieve desired scenario choreography. This synchronization is done with ABD's Synchro software, which is explained in more detail in Section 3.1.

3.1 Synchro System

ABD's Synchro system allows for the synchronization of the motion and position of the actors and the SV. The system consists of a Sync Omni control box and ABD's TrackFi wireless telemetry system.[16] The Sync Omni control box is in the SV and is fed vehicle GPS data. Prior to testing, a procedure is followed to create a local coordinate system in the Synchro software. Communication is established between the SV and the actors using the TrackFi system and is used to provide the local coordinate system from the SV to the actors. This communication also allows for motion and position data to be shared between the two systems in real time. The Sync Omni control box and a TrackFi antenna can be seen in Figure 17.

[16] www.abdynamics.com/en/products/track-testing/wireless-telemetry.

Figure 17. Sync Omni Control Box and TrackFi Antenna

The Synchro system is used to coordinate actor motion with precise timing. The system also allows for CAN data to be collected from the SyncOmni control box. The data includes separate measures of the motion and position of the SV and actors, as well as measures of the relative motion and position of the actors.

3.2 Examples

To demonstrate VRTC's advanced testing system, a few examples of current track tests are presented. Note that most of these examples are primarily for ADAS technologies, but the functions and capabilities needed to complete the scenario are still applicable for testing ADS. These examples demonstrate how VRTC's advanced testing system can be used to create a desired test scenario in the ABD software and execute it on a closed course.

3.2.1 Intersection Safety Assist[17]

Figure 18 shows an example of two straight crossing path (SCP) intersection scenarios. Specific collision timing (crash imminent and near miss) and geometry is required for each scenario. This is achieved by using closed loop control between the SV and POV (i.e., a GST) until the POV reaches its stop bar, after which the POV is operated in open loop. This allows the POV to continue through the intersection without having its speed depend on that of the SV, which is important if the SV's ISA actively applies the brakes to avoid an impact.

[17] https://beta.regulations.gov/document/NHTSA-2019-0102-0006.

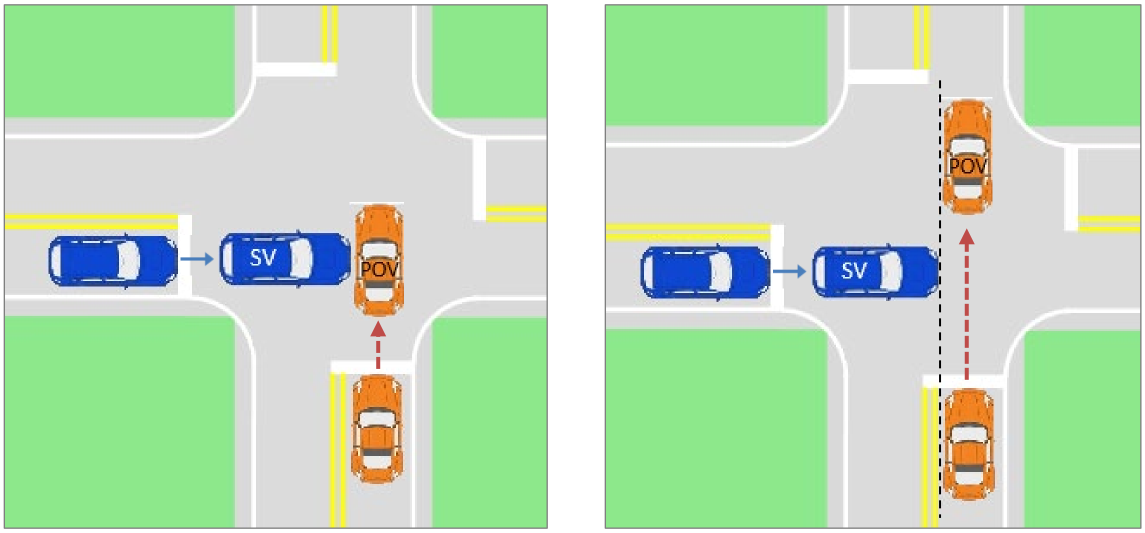


Figure 18. ISA SCP Test Procedure for Crash-Imminent (top left) and Near-Miss (top right)

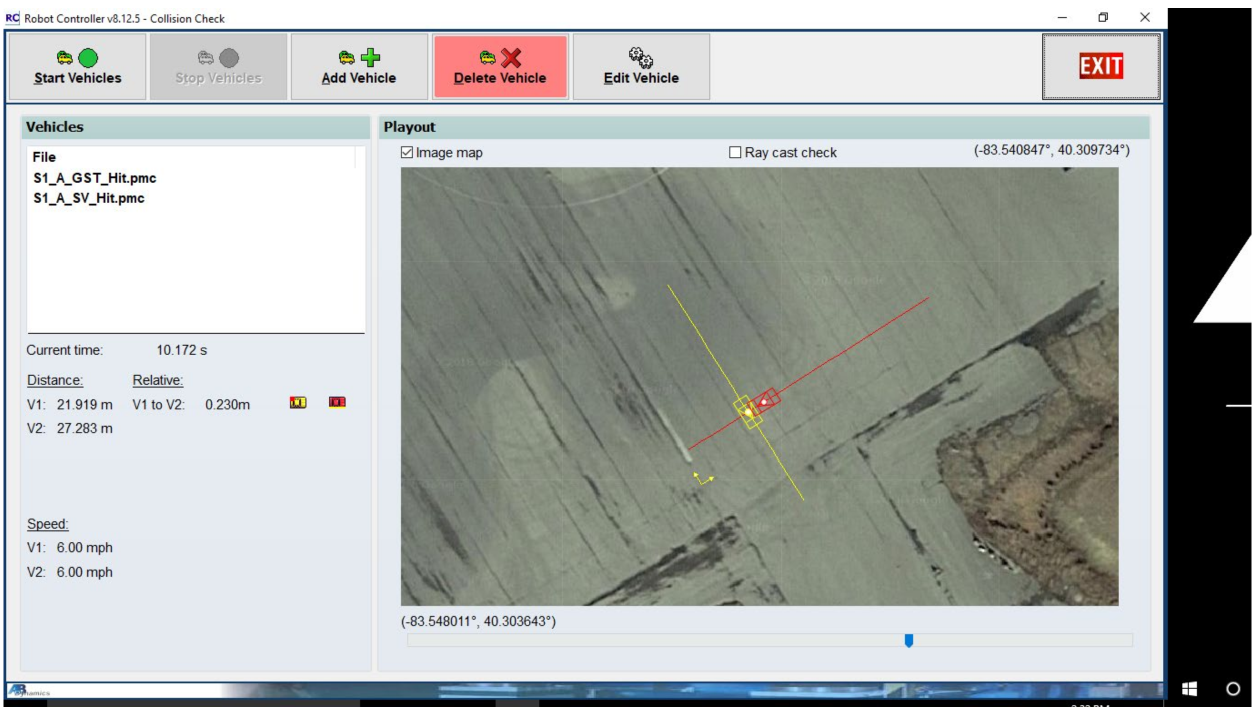


Figure 19. ISA SCP Scenario Creation for Crash-Imminent Timing in ABD Software

Figure 20. Execution of ISA SCP Crash-Imminent Scenario on a Closed-Course Test Track

Figure 21 shows an example of two left turn across path (LTAP) intersection scenarios. Once again, specific collision timing (crash imminent and near miss) and geometry is required for each scenario.

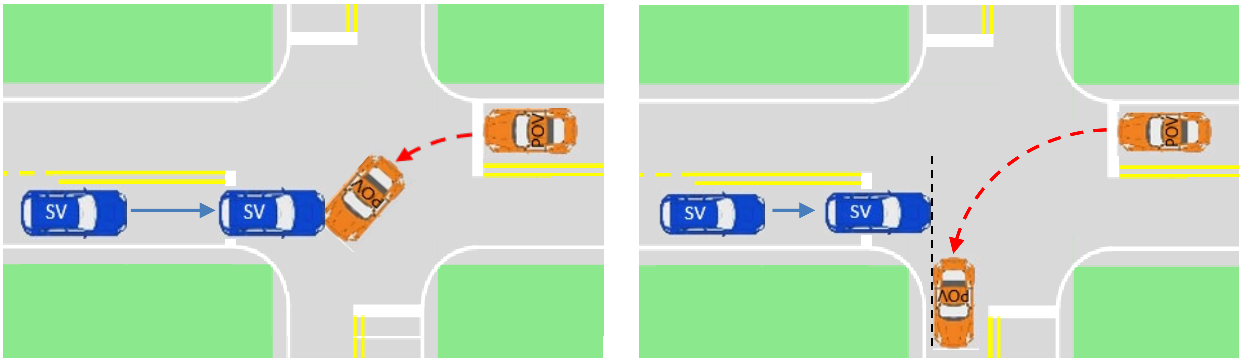


Figure 21. ISA LTAP Test Procedure for Crash-Imminent (top left) and Near-Miss (top right)

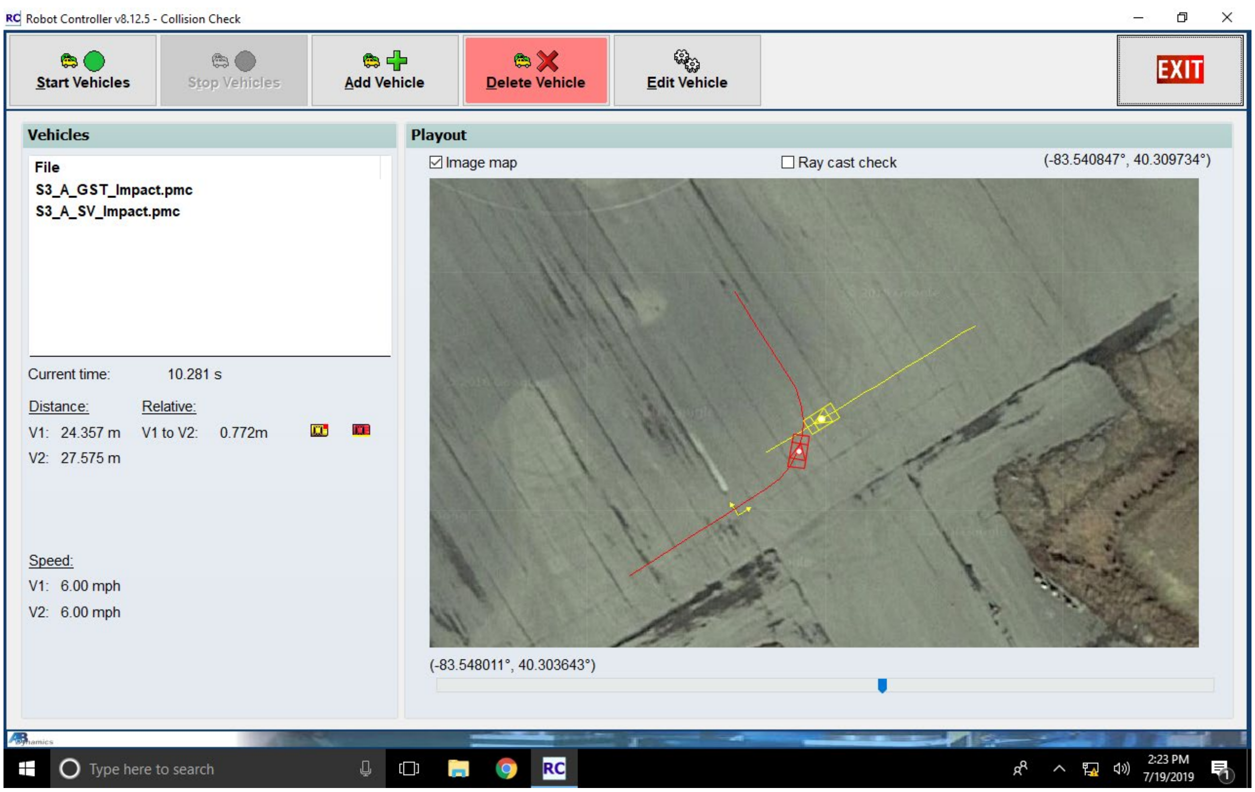


Figure 22. ISA LTAP Scenario Creation for Crash-Imminent Timing in ABD Software

Figure 23. Execution of ISA LTAP Crash-Imminent Scenario on a Closed-Course Test Track

3.2.2 Traffic Jam Assist[18]

Figures 24 and 25 present examples of a suddenly revealed stopped vehicle (SRSV) and lead vehicle lane change with braking (LVLCB) TJA scenarios, respectively. Specific relative position for initiating lane changes is required for both maneuvers. For the LVLCB scenario, the POV needs to be able to switch from closed loop to open loop and perform multiple control actions (lateral lane changing and longitudinal braking) at the same time.

[18] https://beta.regulations.gov/document/NHTSA-2019-0102-0002.

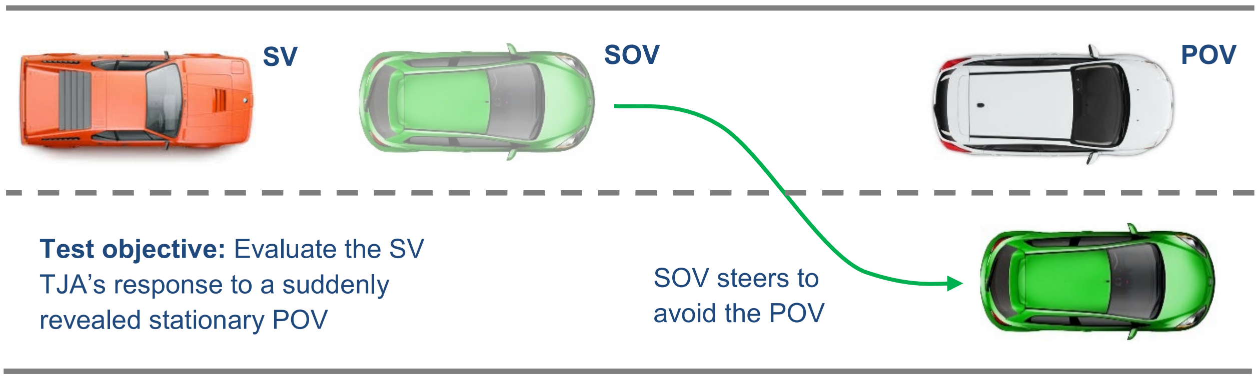


Figure 24. TJA Suddenly Revealed Stopped Vehicle (SRSV) Test Procedure Scenario

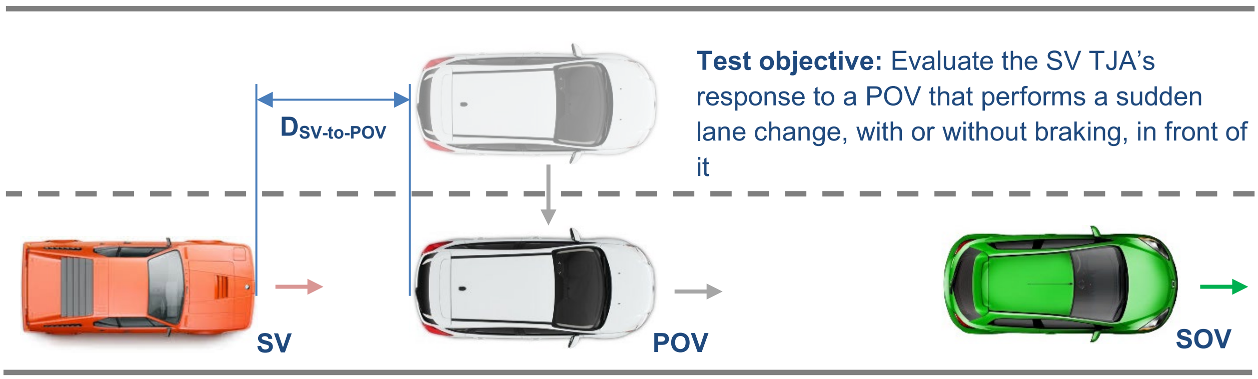


Figure 25. TJA Lead Vehicle Lane Change With Braking (LVLCB) Test Procedure Scenario

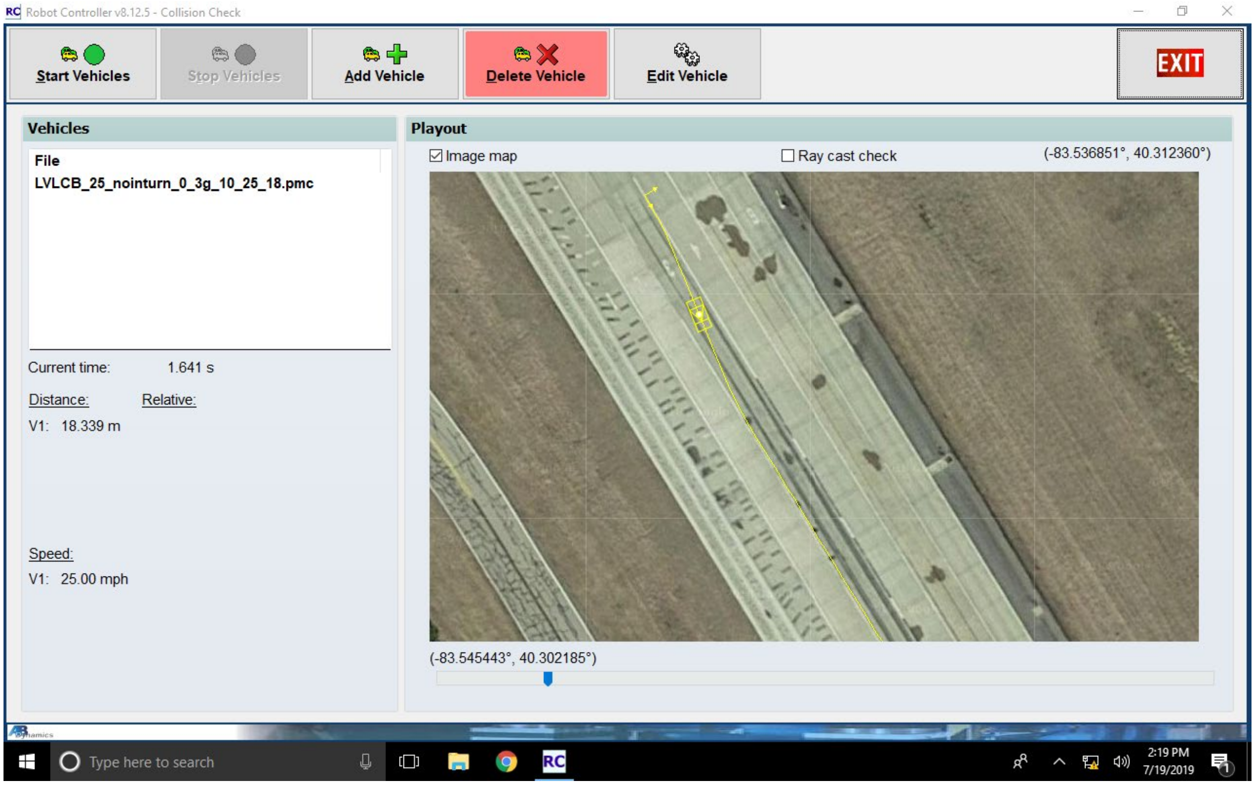


Figure 26. TJA LVLCB Scenario Creation in ABD Software

Figure 27. Execution of TJA SRSV Scenario on a Closed-Course Test Track

3.2.3 Oncoming Traffic Safety Assist

Figure 28 shows an example of an oncoming traffic scenario. This scenario presents a safety critical challenge in that the maneuver is never to be run to the point of a collision. This is accomplished by programming a “bail out” provision into the SV steering robot so that if the SV gets within a certain distance laterally to the GST, the SV is automatically steered away from the impending collision. This requires the steering robot in the SV to go from closed loop control for its lane keeping and execution of the beginning of a lane change with a desired lateral velocity, to open loop to let the SV respond to the scenario without being confounded by the presence of a robotically controlled steering input, back to closed loop if necessary to perform the “bail out” maneuver and regain control of the SV. This scenario is also challenging for the communication between vehicles due to the distance it takes for each vehicle to get up to speed for the scenario.

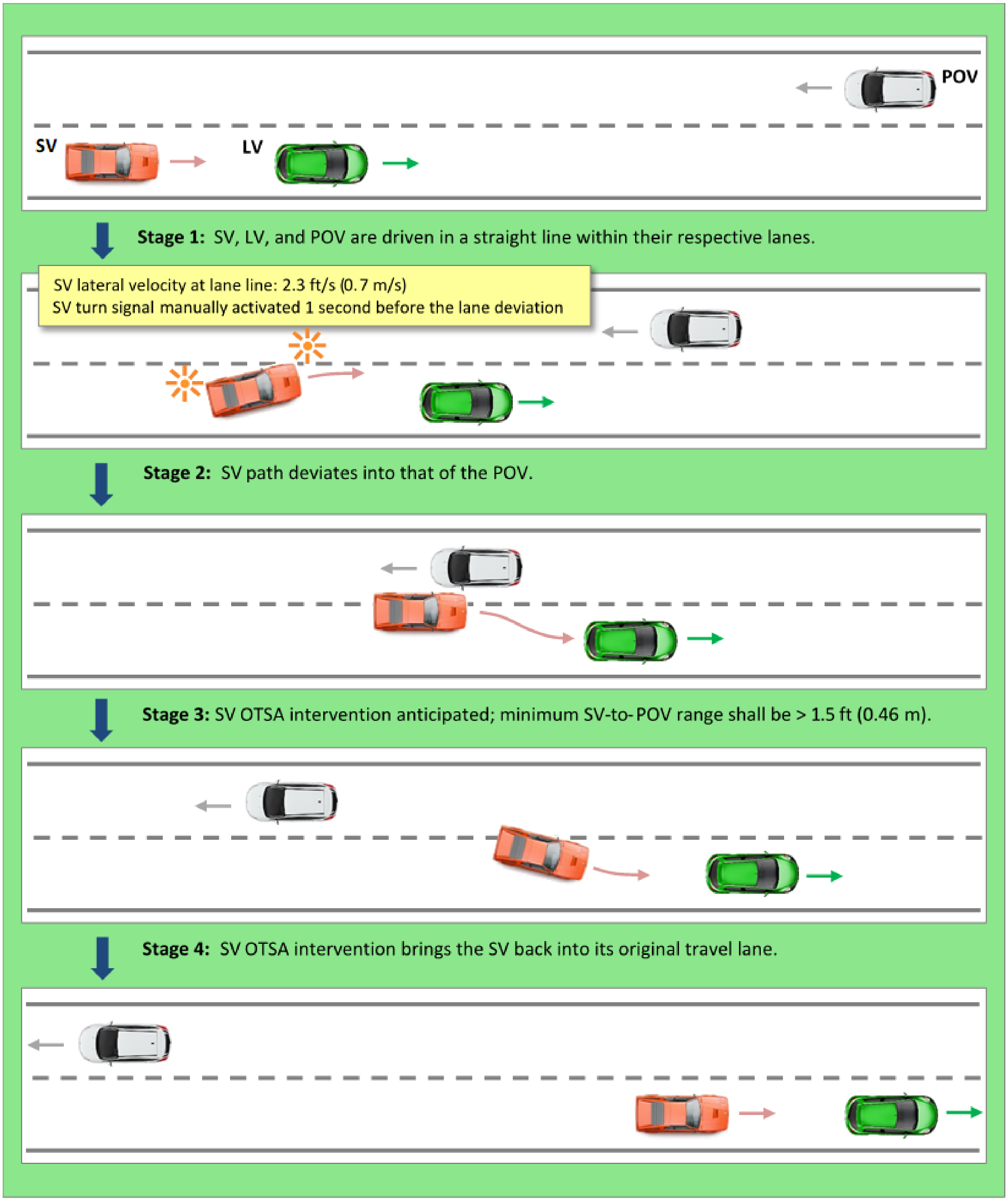


Figure 28. OTSA Test Procedure Scenario

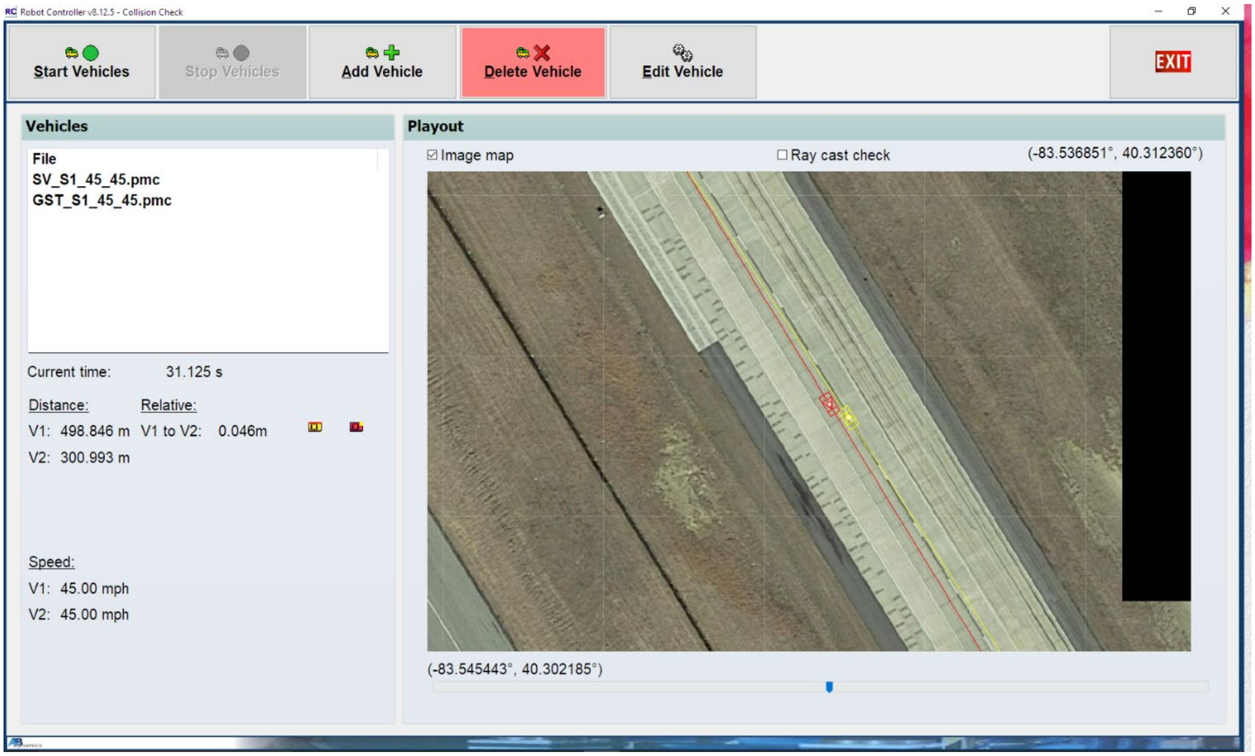


Figure 29. OTSA Scenario Creation in ABD Software

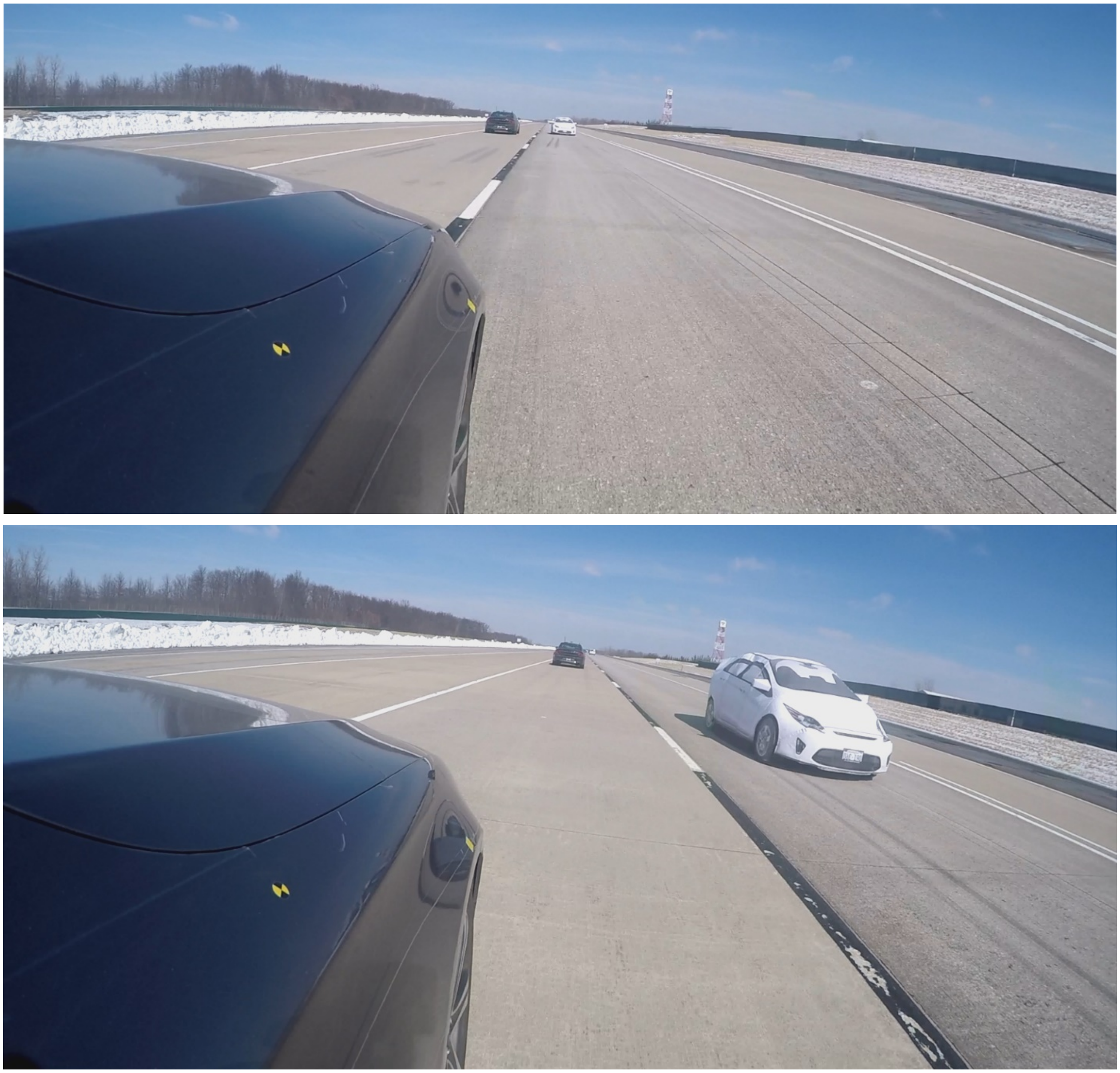


Figure 30. Execution of OTSA Scenario on a Closed-Course Test Track

4. Summary

The advanced testing tools presented in this paper describe VRTC's current capacity for evaluating ADAS and ADS in a closed-course setting. Hardware specifications were developed from an extensive literature review of challenging real-world driving situations along with scenarios that emerging ADAS and/or ADS systems will likely need to safely address. From this, two GSTs, four drop-in kits, one drive-by-wire kit, and surrogate pedestrian apparatus are used to facilitate the testing of these challenging scenarios along with sophisticated control software that allows precise timing and coordination of these actors within a scenario. Data acquisition equipment allows for time synchronized data collection to aid in the analysis of the subsequent data. Additional GPS base stations were also installed to increase the position accuracy of each actor within a scenario.

5. References

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6. Appendix

Table 2. Pre-Crash Scenarios From Najm et al., 2007

Pre-Crash Scenarios	
1	Vehicle Failure
2	Control Loss with Prior Vehicle Action
3	Control Loss without Prior Vehicle Action
4	Running Red Light
5	Running Stop Sign
6	Road Edge Departure with Prior Vehicle Maneuver
7	Road Edge Departure without Prior Vehicle Maneuver
8	Road Edge Departure While Backing Up
9	Animal Crash with Prior Vehicle Maneuver
10	Animal Crash without Prior Vehicle Maneuver
11	Pedestrian Crash with Prior Vehicle Maneuver
12	Pedestrian Crash without Prior Vehicle Maneuver
13	Pedalcyclist Crash with Prior Vehicle Maneuver
14	Pedalcyclist Crash without Prior Vehicle Maneuver
15	Backing Up into Another Vehicle
16	Vehicle(s) Turning – Same Direction
17	Vehicle(s) Parking – Same Direction
18	Vehicle(s) Changing Lanes – Same Direction
19	Vehicle(s) Drifting – Same Direction
20	Vehicle(s) Making a Maneuver – Opposite Direction
21	Vehicle(s) Not Making a Maneuver – Opposite Direction
22	Following Vehicle Making a Maneuver
23	Lead Vehicle Accelerating
24	Lead Vehicle Moving at Lower Constant Speed
25	Lead Vehicle Decelerating
26	Lead Vehicle Stopped
27	Left Turn Across Path from Opposite Directions at Signalized Junctions
28	Vehicle Turning Right at Signalized Junctions
29	Left Turn Across Path from Opposite Directions at Non-Signalized Junctions
30	Straight Crossing Paths at Non-Signalized Junctions
31	Vehicle(s) Turning at Non-Signalized Junctions
32	Evasive Action with Prior Vehicle Maneuver
33	Evasive Action without Prior Vehicle Maneuver
34	Non-Collision Incident
35	Object Crash with Prior Vehicle Maneuver
36	Object Crash without Prior Vehicle Maneuver
37	Other

Table 3. V2V Pre-Crash Scenarios From Najm et al., 2013

Target V2V Pre-Crash Scenarios
Running Red Light
Running Stop Sign
Turning/Same Direction
Changing Lanes/Same Direction
Drifting/Same Direction
Opposite Direction/Maneuver
Opposite Direction/No Maneuver
Rear-End/Striking Maneuver
Rear-End/Lead Vehicle Accelerating (LVA)
Rear-End/Lead Vehicle Moving at Slower Constant Speed (LVM)
Rear-End/Lead Vehicle Decelerating (LVD)
Rear-End/Lead Vehicle Stopped (LVS)
Left Turn Across Path (LTAP)/Opposite Direction (OD) at Signal
Turn Right at Signal
LTAP/OD at Non-Signal
Straight Crossing Path (SCP) at Non-Signal
Turn at Non-Signal

Table 4. California PATH Behavioral Competencies From Nowakowski et al., 2014

Behavioral Competencies	
1	Detect System Engagement/Disengagement Conditions Including Limitations by Location, Operating Condition, or Component Malfunction
2	Detect & Respond to Speed Limit Changes (Including Advisory Speed Zones)
3	Detect Passing and No Passing Zones
4	Detect Work Zones, Temporary Lane Shifts, or Safety Officials Manually Directing Traffic
5	Detect and Respond to Traffic Control Devices
6	Detect and Respond to Access Restrictions such as One-Way Streets, No-Turn Locations, Bicycle Lanes, Transit Lanes, and Pedestrian Ways
7	Perform High Speed Freeway Merge
8	Perform a Lane Change or Lower Speed Merge
9	Park on the Shoulder or Transition the Vehicle to a Minimal Risk State (Not Required for SAE Level 3)
10	Navigate Intersections & Perform Turns
11	Navigate a Parking Lot & Locate Open Spaces
12	Perform Car Following Including Stop & Go and Emergency Braking
13	Detect & Respond to Stopped Vehicles
14	Detect & Respond to Intended Lane Changes / Cut-Ins
15	Detect & Respond to Encroaching Oncoming Vehicles
16	Detect & Respond to Static Obstacles in Roadway
17	Detect & Respond to Bicycles, Pedestrians, Animals, or Other Moving Objects
18	Detect Emergency Vehicles

Table 5. Federal Automated Vehicle Policy Behavioral Competencies From U.S. Department of Transportation, 2016

Behavioral Competencies	
1	Detect and Respond to Speed Limit Changes and Speed Advisories
2	Perform High-Speed Merge (e.g., Freeway)
3	Perform Low-Speed Merge
4	Move Out of the Travel Lane and Park (e.g., to the Shoulder for Minimal Risk)
5	Detect and Respond to Encroaching Oncoming Vehicles
6	Detect Passing and No Passing Zones and Perform Passing Maneuvers
7	Perform Car Following (Including Stop and Go)
8	Detect and Respond to Stopped Vehicles
9	Detect and Respond to Lane Changes
10	Detect and Respond to Static Obstacles in the Path of the Vehicle
11	Detect Traffic Signals and Stop/Yield Signs
12	Respond to Traffic Signals and Stop/Yield Signs
13	Navigate Intersections and Perform Turns
14	Navigate Roundabouts
15	Navigate a Parking Lot and Locate Spaces
16	Detect and Respond to Access Restrictions (One-Way, No Turn, Ramps, etc.)
17	Detect and Respond to Work Zones and People Directing Traffic in Unplanned or Planned Events
18	Make Appropriate Right-of-Way Decisions
19	Follow Local and State Driving Laws
20	Follow Police/First Responder Controlling Traffic (Overriding or Acting as Traffic Control Device)
21	Follow Construction Zone Workers Controlling Traffic Patterns (Slow/Stop Sign Holders).
22	Respond to Citizens Directing Traffic After a Crash
23	Detect and Respond to Temporary Traffic Control Devices
24	Detect and Respond to Emergency Vehicles
25	Yield for Law Enforcement, EMT, Fire, and Other Emergency Vehicles at Intersections, Junctions, and Other Traffic Controlled Situations
26	Yield to Pedestrians and Bicyclists at Intersections and Crosswalks
27	Provide Safe Distance from Vehicles, Pedestrians, Bicyclists on Side of the Road
28	Detect/Respond to Detours and/or Other Temporary Changes in Traffic Patterns

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