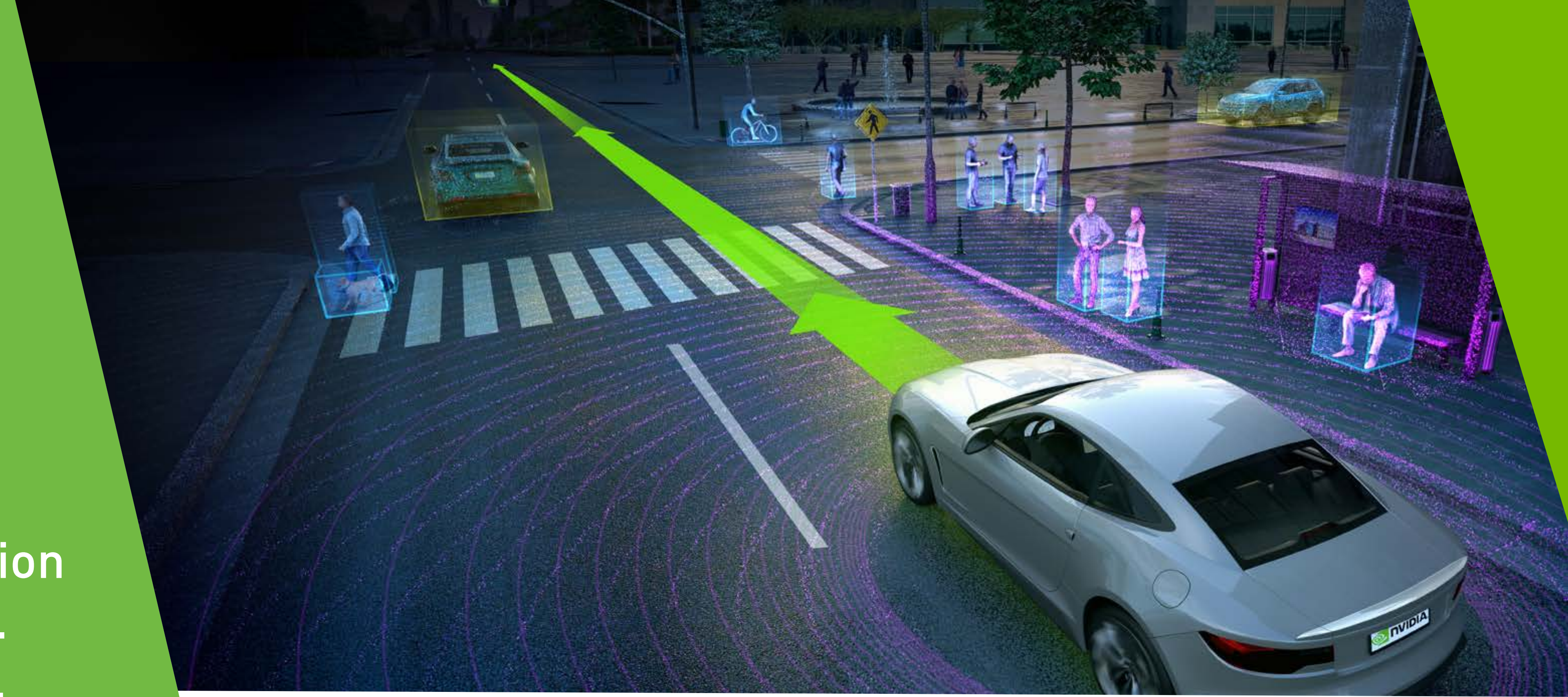
SELF-DRIVING SAFETY REPORT

OUR MISSION

We believe that the next generation of transportation is autonomous. From shared and personal vehicles, to long- and short-distance travel, to delivery and logistics, autonomy will fundamentally improve the way the world moves. At NVIDIA, our automotive team's mission is to develop self-driving technology that enables safer, less congested roads and mobility for all.



"Safety is the most important aspect of a self-driving vehicle. NVIDIA's creation of a safe, self-driving platform is one of our greatest endeavors, and provides a critical ingredient for automakers to bring autonomous vehicles to market."

Jensen Huang
NVIDIA founder and CEO

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INTRODUCTION

Two decades ago, NVIDIA invented the GPU, sparking a revolution in computing. This core technology was born in the gaming and professional visualization industries, and has now translated to revolutionary leaps in high-performance and accelerated computing, as well as artificial intelligence (AI). As we've scaled our business and taken on new challenges, our systems and products have pushed boundaries in robotics, healthcare, medicine, space exploration, and entertainment. NVIDIA is now applying our futuristic vision, computational performance, and energy efficiency to the transportation industry—helping automakers around the world realize the dream of safe, reliable autonomous vehicles.

Autonomous vehicles are transforming the transportation industry. They have the potential to save lives by drastically reducing vehicle-related accidents, reduce traffic congestion and energy consumption, increase productivity, and provide mobility to those who are unable to drive. NVIDIA partners with automakers, suppliers, sensor manufacturers, mapping companies, and startups around the world to develop the best solutions for the new world of mobility. We provide the systems architecture, AI supercomputing hardware, and core software required to build all types of autonomous vehicles—from automated cars and trucks to fully autonomous shuttles and robotaxis.

It all starts with NVIDIA DRIVE™, our highly scalable platform that can enable all levels of autonomous driving as defined by the Society of Automotive Engineers (SAE). These range from advanced driver-assistance system features (SAE Level 2: driver-assisted) through robotaxis (SAE Level 5: full automation).

The computational requirements of fully autonomous driving are enormous—easily up to 100 times higher than the most advanced vehicles in production today. With NVIDIA DRIVE, our partners achieve an increase in safety, running sophisticated software with many levels of diverse and redundant algorithms, in real-time.

To streamline development, we've created a single scalable architecture that advances each level of autonomy with additional hardware and software while preserving the core architecture. The same strategy holds for safety. Our architecture enriches the overall system with elements to consistently improve safety.

NVIDIA has created essential technologies for building robust, end-to-end systems for the research, development, and deployment of self-driving vehicles. We offer a range of hardware and software solutions, from powerful GPUs and servers to a complete AI training infrastructure and in-vehicle autonomous driving supercomputer. We also support academic research and early-stage developers, partnering with dozens of universities worldwide and teaching courses on AI development at our Deep Learning Institute. As we identify challenges, we turn them into opportunities and build solutions.

This report provides an overview of NVIDIA's autonomous vehicle technologies and how our unique contributions in safety architecture, co-designed hardware and software, design tools, methodologies, and best practices enable the highest possible levels of reliability and safety.

The underlying principle for safety is to introduce redundancy and diversity into the system. NVIDIA applies this principle when architecting processors and computing platforms, designing algorithms for driving and mapping, and integrating sensors into the vehicle. We address safety at every phase of AV development and design in the computational requirements to achieve the highest quality levels.

As an example, a car equipped with 10 high-resolution cameras generates 2 gigapixels per second of data. Processing that data through multiple deep neural networks converts to approximately 250 TOPS (trillion operations per second). Add other sensor types and in-vehicle AI, and that performance requirement increases. For self-driving cars, compute translates to safety[1].

THE BENEFITS OF SELF-DRIVING VEHICLES

Data collected by the U.S. Department of Transportation in 2016 highlights the urgent need for autonomous driving solutions. The number of road deaths increased by 5.6 percent over the previous year—more than in any of the previous 50 years[2]. The National Highway Traffic Safety Administration estimates that 94 percent of traffic accidents[3] are caused by human error, including distracted driving, drowsiness, speeding, and alcohol impairment.

Fortunately, technology that augments or replaces the driver can mitigate the vast majority of those incidents. It can also significantly reduce the number of hours commuters waste in traffic each year (currently averaging 42 hours) and the $160 billion lost to traffic congestion[4]. Additionally, automated driving leads to more efficient traffic patterns, so it can reduce the amount of air pollution the transportation industry contributes, estimated in 2016 to be 28 percent of all U.S. greenhouse gas emissions[5].

COMPUTE ENABLES GREATER SAFETY

NVIDIA uniquely provides the high-performance computing necessary to enable redundant sensors, diverse algorithms, and additional diagnostics to support safer operation. We equip cars with many types of redundant sensors for sensor fusion. Then, multiple diverse AI deep neural networks and algorithms for perception, mapping localization, and path planning are run on a combination of integrated GPUs, CPUs, deep learning accelerators (DLAs), and programmable vision accelerators (PVAs) for the safest possible driving.

THE FOUR PILLARS OF SAFE AUTONOMOUS DRIVING

NVIDIA offers a unified hardware and software architecture throughout its autonomous vehicle research, design, and deployment infrastructure. We deliver the technology to address the four major pillars essential to making safe self-driving vehicles a reality.

PILLAR 1

ARTIFICIAL INTELLIGENCE DESIGN AND IMPLEMENTATION PLATFORM

PILLAR 2

DEVELOPMENT INFRASTRUCTURE THAT SUPPORTS DEEP LEARNING

PILLAR 3

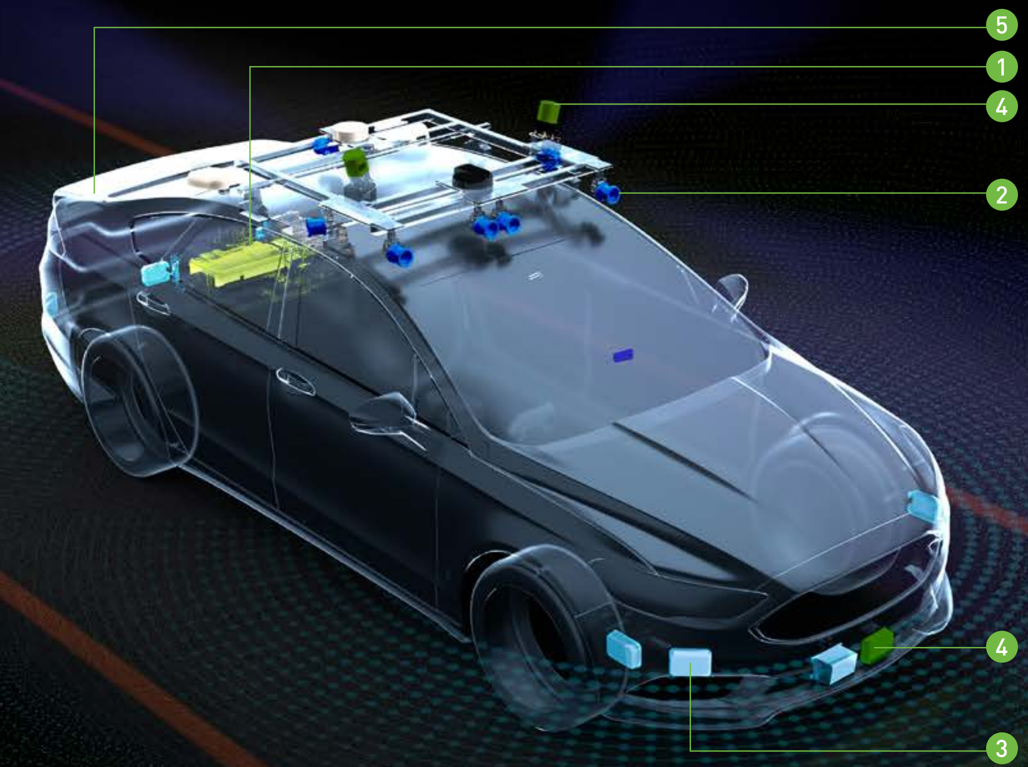
DATA CENTER SOLUTION FOR ROBUST SIMULATION AND TESTING

PILLAR 4

BEST-IN-CLASS PERVASIVE SAFETY PROGRAM

This report details each of these pillars and how our autonomous vehicle safety program addresses industry guidelines and standards.

HOW DOES AN AUTONOMOUS VEHICLE WORK?



1. **DRIVE AGX Platform**
   Sensor processing, AI computations, path planning, vehicle control
2. **Camera**
   Detection and classification of static (signs, lanes, boundaries, etc.) and dynamic objects (pedestrians, cyclists, collision-free space, hazards, etc.)
3. **Radar**
   Detection of motion in a wide range of light and weather conditions
4. **Lidar**
   High-precision detection in all light conditions
5. **GNSS & IMU**
   Rough positioning and motion compensation for some sensors

A fully autonomous vehicle can drive on its own through a combination of functionalities: perception, sensor fusion, localization to a high-definition map, path planning, and actuation. Cameras, radar, and lidar sensors let the vehicle see the 360-degree world around it, detecting traffic signals, pedestrians, vehicles, infrastructure, and other vital information. An on-board AI supercomputer interprets that data in real-time and combines it with cloud-based, high-definition mapping systems to safely navigate an optimal route. This self-driving system allows the vehicle to detect and anticipate how objects and people along its path are moving, and then automatically control the vehicle's steering, acceleration, and braking systems. The AI systems are capable of superhuman levels of perception and performance. They track all activity around the vehicle, and never get tired, distracted, or impaired. The result is increased safety on our roads.

PILLAR 1

ARTIFICIAL INTELLIGENCE DESIGN AND IMPLEMENTATION PLATFORM

NVIDIA DRIVE is the world's first scalable AI platform that spans the entire range of autonomous driving, from assisted highway driving to robotaxis. It consists of hardware, software, and firmware that work together to enable the production of automated and self-driving vehicles.

Our platform combines deep learning, sensor fusion, and surround vision to enable a safe driving experience. With high-performance computing, the vehicle can understand in real-time what's happening around it, precisely localize itself on a high-definition map, and plan a safe path forward. Designed around a diverse and redundant system architecture, our platform is built to support the highest level of automotive functional safety, for systems scaling from premium ADAS to fully autonomous robotaxis.

Our unified architecture extends from the data center to the vehicle and provides an end-to-end solution that will conform to national and international safety standards. Deep neural networks (DNNs) can be trained on a GPU-based server in the data center, then fully tested and validated in simulation before seamlessly deployed to run on our AI computer in the vehicle.

To safely operate, self-driving vehicles require supercomputers powerful enough to process all the sensor data in real time. Our underlying hardware solutions include:

DRIVE AGX Xavier™

An in-vehicle supercomputer based on NVIDIA Xavier, the world's first in-vehicle AI SoC (system on a chip) designed for autonomous machines. This platform can simultaneously run numerous DNNs to provide safety and reliability.

DRIVE AGX Pegasus™

A higher-performance AI supercomputer that integrates multiple Xavier SoCs and multiple GPUs, delivering the diversity and redundancy required for fully autonomous driving.

NVIDIA® DGX™ AI Supercomputers

A fully integrated data-center-based deep learning system for AI model development and validation (See also pillars 3 and 4).

The architecture of NVIDIA Xavier, the world's first single-chip autonomous vehicle processor, has been assessed by top safety experts at German agency TÜV SÜD as suitable for AVs. NVIDIA's ASIC development process is also certified ISO 26262-compliant".[4]

NVIDIA DRIVE software enables our customers to develop production-quality applications for automated and autonomous vehicles. It contains software modules, libraries, frameworks, and source packages that developers and researchers can use to optimize, validate, and deploy their work. Our foundational software products include:

DRIVE OS

The underlying real-time operating system system software includes a safety application framework, and offers support of Adaptive AUTOSAR.

DRIVE AR

The perception visualization software stack is used to build cockpit experiences for dashboard and back-seat screens. It takes complex information from the vehicle's sensors and transforms it into comprehensive and accurate visuals that are easily understood, helping passengers build trust in the AV technology.

DRIVE AV

The autonomous vehicle driving system software integrates a diverse range of DNNs for detection of all types of environments, and objects within those environments, along with vehicle localization and path-planning algorithms.

DRIVE Hyperion

This complete AV development and testing platform includes a DRIVE AGX Pegasus system, along with sensors for autonomous driving (seven cameras, eight radars, and optional lidars), sensors for driver monitoring, sensors for localization, and other accessories.

DRIVE IX

This deep learning-based software stack enables manufacturers to develop intelligent experiences inside the vehicle, from driver-monitoring systems using in-cabin cameras to voice and gesture-activated AI assistants.

DRIVE Mapping

The mapping solution integrates a scalable sensor suite, software development kits (SDKs), and co-integrated high-definition maps available through partnerships with leading mapping companies. Our end-to-end mapping technologies help collect environment data, create HD maps, and keep them updated.

Additional NVIDIA DRIVE hardware and software solutions are highlighted in pillars 2 and 3.

The NVIDIA DRIVE AGX architecture enables vehicle manufacturers to build and deploy self-driving cars and trucks that are functionally safe and can be demonstrated compliant to international safety standards such as ISO 26262 and ISO/PAS 21448, NHTSA recommendations, and global NCAP requirements.

\ SAFETY REQUIRES HIGH-PERFORMANCE COMPUTING

For self-driving cars, processing performance translates to safety. The more compute, the more sophisticated the algorithm, the more layers in a deep neural network and the greater number of simultaneous DNNs that can be run. NVIDIA offers an unprecedented 320 trillion operations persecond of deep learning compute on DRIVE AGX Pegasus.

PILLAR 2

DEVELOPMENT INFRASTRUCTURE THAT SUPPORTS DEEP LEARNING

In addition to in-vehicle supercomputing hardware, NVIDIA solutions power the data centers used to solve critical challenges faced in the development of safe AVs. A single test vehicle can generate petabytes of data each year. Capturing, managing, and processing this massive amount of data for not just one car, but a fleet, requires an entirely new computing architecture and infrastructure.

NVIDIA DRIVE Perception Infrastructure delivers and supports massive data collection, deep learning development, and traceability to support large autonomous fleets. It runs on the NVIDIA DGX SaturnV—our AI supercomputer comprised of 660 NVIDIA DGX-1™ systems with 5280 GPUs—and is capable of 660 petaflops for AI model development and training.

Our AI infrastructure helps developers create and quickly train DNN models to enable highly accurate perception systems for autonomous vehicles. For example, we used the DRIVE Perception Infrastructure to create dozens of neural networks that separately cover perception of lanes and road boundaries, road markings, signs, vehicles, wait conditions, free space, and more.

The ideal AI computing infrastructure helps build safe systems using data from various on-vehicle sensors. We enable camera-based perception and mapping, lidar-based perception and mapping, camera-based localization to high-definition maps, lidar-based localization to high-definition maps, and more.

DRIVE Perception Infrastructure also allows for deep learning processing, which is assisted by qualified tools like the deep learning compilers and runtime engines that NVIDIA rebuilt to fulfill automotive-grade requirements.

PILLAR 3

DATA CENTER SOLUTION FOR ROBUST SIMULATION AND TESTING

Before any autonomous vehicle can safely navigate on the road, engineers must first test and validate the AI algorithms and other software that enable the vehicle to drive itself. AI-powered autonomous vehicles must be able to respond properly to the incredibly diverse situations they could experience, such as emergency vehicles, pedestrians, animals, and a virtually infinite number of other obstacles—including scenarios that are too dangerous to test in the real world.

In addition, AVs must perform regardless of weather, road, or lighting conditions. There's no feasible way to physically road test vehicles in all these situations, nor is road testing sufficiently controllable, repeatable, exhaustive, or fast enough. The ability to test in a realistic simulation environment is essential to providing safe self-driving vehicles. Coupling actual road miles with simulated miles in the data center is the key to testing and validating AVs.

NVIDIA DRIVE Constellation™ is a data center solution that enables developers to test and validate the actual hardware and software that will operate in an autonomous vehicle before it's deployed on the road. The platform is comprised of two side-by-side servers, with the first using NVIDIA GPUs running DRIVE Sim™ software to simulate sensor data from cameras, radars, and lidars on a virtual car driving in a virtual world. The output of the simulator is fed into the second server containing the DRIVE AGX Pegasus AI car computer running the complete AV software stack and processing the simulated sensor data.

The driving decisions from DRIVE AGX Pegasus are fed back to the simulator 30 times every second, enabling hardware-in-the-loop testing. DRIVE Constellation and the DRIVE Sim can simulate rare and dangerous scenarios at a scale simply not possible with on-road test drives. The platform is capable of simulating billions of miles in virtual reality, running repeatable regression tests, and validating the complete AV system.

PILLAR 4

BEST-IN-CLASS PERVASIVE SAFETY PROGRAM

Safety is our highest priority at every step of the research, development, and deployment process. It begins with a pervasive safety methodology that emphasizes diversity and redundancy in the design, validation, verification, and lifetime support of the entire autonomous system. We settle for nothing less than best-in-class solutions in our processes, products, and safety architecture.

To conceptualize our autonomous vehicle safety program, we follow recommendations by the U.S. Department of Transportation's National Highway Traffic Safety Administration in its 2017 [3] and 2018 [12] publications.

Throughout our program, we benchmark ourselves against the automotive industry's highest safety standards from the International Organization for Standardization (see sidebar). These are:

Functional Safety and Safety of the Intended Functionality (SOTIF)

Autonomous vehicles must be able to operate safely, even when a system fails. Functional safety focuses on measures to ensure risk is minimized when hardware, software, or systems fail to work as intended.

Safety hazards can be present even if the system is functioning as designed, without a malfunction. SOTIF focuses on ensuring the absence of unreasonable risk due to hazards resulting from insufficiencies in the intended functionality or from reasonably foreseeable misuse.

Federal and International Regulations

We also adhere to federal and international regulations, including global NCAP (New Car Assessment Program), Euro NCAP, and the United Nations Economic Commission for Europe. We influence, co-create, and follow standards of the International Standards Organization, the New Vehicle Assessment Program, and the Society of Automotive Engineers International, as well as standards from other industries.

Beyond complying with federal and industry guidelines, we practice open disclosure and collaboration with industry experts to ensure that we remain up-to-date on all current and future safety issues. We also hold leadership positions in multiple safety working groups to drive the state-of-the-art and explore new research areas, such as safety for AI systems and explainable AI[7].

The NVIDIA DRIVE AGX architecture is designed to support Levels 2 through 5 of the SAE J3016 specification and includes support of NCAP.

NATIONAL AND INTERNATIONAL SAFETY REGULATIONS AND RECOMMENDATIONS

NVIDIA adheres to national and international safety recommendations outlined here.

International Organization for Standardization (ISO)

Functional Safety

ISO 26262[8] addresses functional safety in road vehicles. It focuses on avoiding failures that can be avoided, while detecting and responding appropriately to unavoidable failures due to malfunction. This is done through combinations of robust processes during development, production, and operation, as well as inclusion of diagnostics and other mitigations to manage random hardware failures. ISO 26262 can be applied at the vehicle, system, hardware, and software levels.

Safety of the Intended Functionality (SOTIF)

ISO/PAS 21448[9] addresses safety of the intended functionality in road vehicles. It reuses and extends the ISO 26262 development process to address SOTIF concerns. Safety hazards are evaluated for vehicle behavior and known system limitations and mitigations are defined, implemented, and verified during development. Before release, the safety of the vehicle system is validated to ensure that no unreasonable risk remains.

National Highway Traffic Safety Administration (NHTSA)
Safety guidelines for autonomous driving are covered in a publication released by NHTSA titled Voluntary Guidance for Automated Driving Systems[3]. Because NVIDIA is not a vehicle manufacturer, a few of safety elements, such as crashworthiness and whiplash/rear-end crash protection, are not explicitly covered in this report. Of the 12 safety elements representing industry consensus on safety for the use of automated driving systems on public roadways, 10 are the most relevant to NVIDIA:

- System Safety
- Operational Design Domain
- Object And Event Detection and Response
- Fallback (Minimal Risk Condition)
- Validation Methods
- Data Recording
- Human-Machine Interface
- Vehicle Cybersecurity
- Consumer Education and Training
- Federal, State, and Local Laws

Global NCAP
Regional NCAPs adjust safety practices to their particular markets, and NVIDIA complies with all local NCAP versions. The European New Vehicle Assessment Program (Euro NCAP) provides consumers with an independent safety assessment of vehicles sold in Europe. Euro NCAP published its 2025 Roadmap[10], which presents a vision and strategy to emphasize primary, secondary, and tertiary vehicle safety. We are currently addressing these Euro NCAP recommendations:

- Automatic Emergency Steering
- Automated Driving Testing and Assessment
- Autonomous Emergency Braking
- V2X
- Driver Monitoring
- Human-Machine Interface (HMI)
- Pedestrian and Cyclist Safety
- Simulation
- Child Presence Detection
- Cybersecurity
- Rescue, Extrication, and Safety
- Truck Safety

\ The NVIDIA Solution – NHTSA Safety Element

SYSTEM SAFETY

NVIDIA has created a system safety program that integrates robust design and validation processes based on a systems-engineering approach with the goal of designing automated driving systems with the highest level of safety and free of unreasonable safety risks.

\ The NVIDIA Solution – NHTSA Safety Element

FALLBACK (MINIMAL RISK CONDITION)

Our products enable the vehicle to detect a system malfunction or breach of the operational design domain, and then transition the system to a safe or degraded mode of operation based on warning and degradation strategy. Every NVIDIA autonomous driving system includes a fallback strategy that enables the driver to regain proper control of the vehicle or allows the autonomous vehicle to return to a minimal risk condition independently. Our HMI products can be used to notify the driver of a potentially dangerous event and return the vehicle to a minimal risk condition independently, or alert the driver to regain proper control. The minimal risk conditions vary according to the type and extent of a given failure.

\ The NVIDIA Solution – NHTSA Safety Element

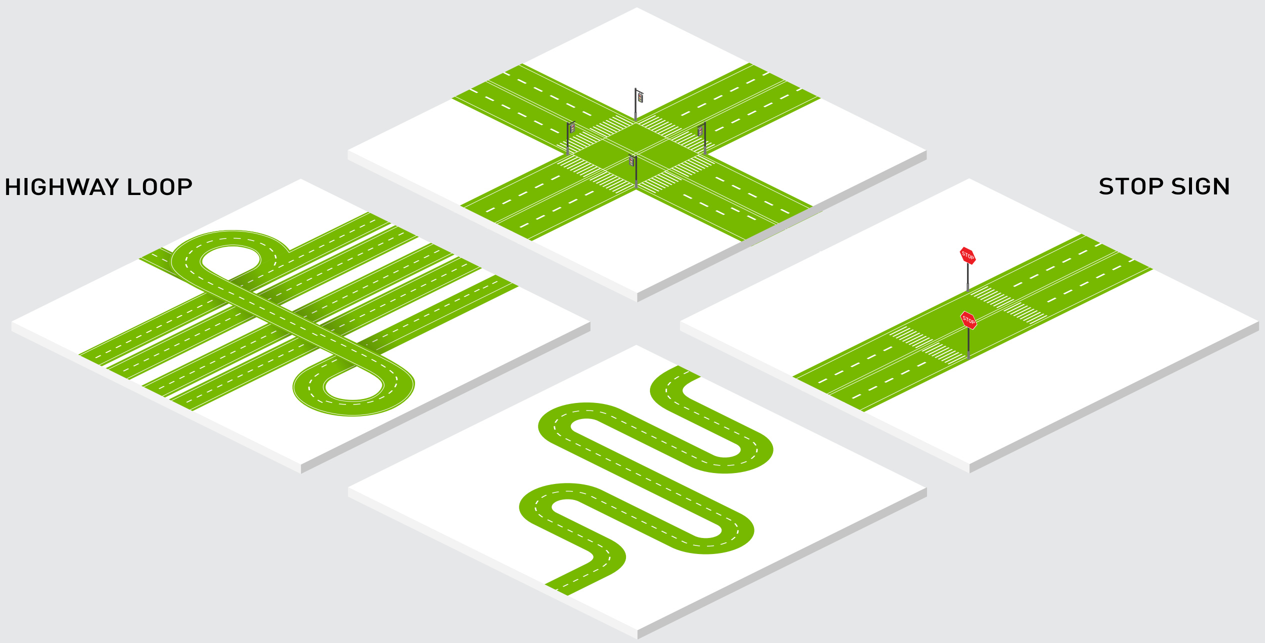
VALIDATION METHODS

Validation methods establish confidence that the autonomous system can accomplish its expected functionalities. Our development process contains rigorous methods to verify and validate our products' behavioral functionality and deployment. To demonstrate the expected performance of an autonomous vehicle for deployment on public roads, our test approaches include a combination of simulation, test track, and on-road testing. These methods expose the performance under widely variable conditions, such as when deploying fallback strategies.

\ The NVIDIA Solution – NHTSA Safety Element

OPERATIONAL DESIGN DOMAIN

NVIDIA has developed an extensive set of operational design domains as recommended by NHTSA. Each operational design domain includes the following information at a minimum to define the product's capability boundaries: roadway types, geographic area and geo-region conditions, speed range, environmental conditions (weather, time of day, and so forth), and other constraints.



ARCHITECTED FOR SAFETY

NVIDIA designs the DRIVE AGX platform to ensure that the autonomous vehicle can operate safely within the operational design domain for which it is intended. In situations where the vehicle is outside its defined operational design domain or conditions dynamically change to fall outside it, our products enable the vehicle to return to a minimal risk condition (also known as a safe fallback state). For example, if an automated system detects a sudden change such as a heavy rainfall that affects the sensors and, therefore, the driving capability within its operational design domain, the system is designed to hand off control to the driver. If significant danger is detected, the system is designed to come to a safe stop.

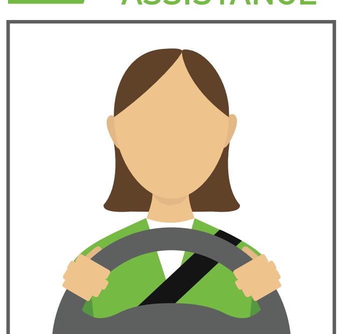
NVIDIA follows the V-model (including verification and validation) at every stage of DRIVE development. We also perform detailed analyses of our products' functionality and related hazards to develop safety goals for the product. For each identified hazard, we create safety goals to mitigate risk, each rated with an Automotive Safety Integrity Level (ASIL). ASIL levels of A, B, C, or D indicate the level of risk mitigation needed, with ASIL D representing the safest (the highest level of risk reduction). Meeting these safety goals is the top-level requirement for our design. By applying the safety goals to a functional design description, we create more detailed functional safety requirements.

L1 NO AUTOMATION

Zero autonomy

Driver performs all driving tasks

L2 DRIVER ASSISTANCE



Vehicle has some function-specific assist automation

Driver performs all driving tasks

L3 CONDITIONAL AUTOMATION

Vehicle can monitor and respond to its environment

Driver must be ready to take control when alerted

At the system-development level, we refine the safety design by applying the functional safety requirements to a specific system architecture. Technical analyses –such as failure mode and effects analysis (FMEA), fault tree analysis (FTA), and dependent failure analysis (DFA)–are applied iteratively to identify weak points and improve the design. Resulting technical safety requirements are delivered to the hardware and software teams for development at the next level. We've also designed redundant and diverse functionality into our autonomous vehicle system to make it as resilient as possible. This ensures that the vehicle will continue to operate safely when a fault is detected or reconfigure itself to compensate for a fault.

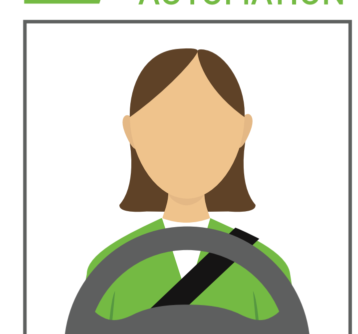
At the hardware-development level, we refine the overall design by applying technical safety requirements to the hardware designs of the board and the chip (SoC or GPU). Technical analyses are used to identify any weak points and improve the hardware design. Analysis of the final hardware design is used to verify that hardware failure related risks are sufficiently mitigated.

At the software-development level, we consider both software and firmware. We refine the overall design by applying technical safety requirements to the software architecture. We also perform code inspection, reviews, automated code structural testing, and code functional testing at both unit and integration levels. Software-specific failure mode and effects analysis are used to design better software. In addition, we design test cases for interface, requirements-based, fault injection, and resource usage validation methods.

When we have all necessary hardware and software components complete, we integrate and start our verification and validation processes on the system level.

In addition to the autonomous vehicle simulation described under Simulation, we also perform end-to-end system testing and validation.

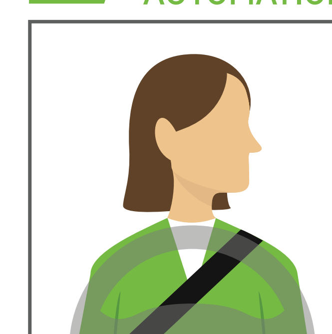
L4 HIGH AUTOMATION



Vehicle can perform all driving functions under certain conditions

Driver has the option to control the vehicle

L5 FULL AUTOMATION



Vehicle can perform all driving functions under all conditions

Driver may have the option to control the vehicle

ALL IN ONE: AI TRAINING, SIMULATION, AND TESTING

NVIDIA's infrastructure platform enables the training, simulating, and testing of autonomous driving applications. This includes a data factory to label millions of images, NVIDIA DGX SaturnV supercomputer for training DNNs, DRIVE Constellation for hardware-in-the-loop simulation, and other tools to complete our end-to-end system.

Autonomous vehicle software development begins with collecting huge amounts of data from vehicles in globally diverse environments and situations. Multiple teams across many geographies access this data for labeling, indexing, archiving, and management before it can be used for AI model training and validation. We call this first step of the autonomous vehicle workflow the "data factory."

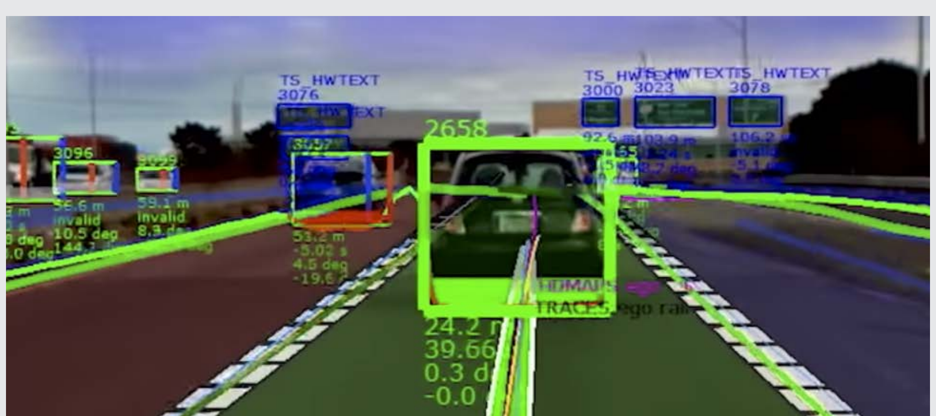
AI model training starts when the labeled data is used to train them for perception and other self-driving functions. This is an iterative process; the initial models are used by the data factory to select the next set of data to be labeled. Deep learning engineers adjust model parameters as needed, and then re-train the DNN, at which point the next set of labeled data is added to the training set. This process continues until the desired model performance and accuracy is achieved.

Self-driving technology must be evaluated again and again during development in a vast array of driving conditions to ensure that the vehicles are far safer than human-driven vehicles. Simulation runs test-drive scenarios in a virtual world, providing rendered sensor data to the driving stack and carrying out driving commands from the driving stack. Re-simulation plays back previously recorded sensor data to the driving stack. The AI model is finally validated against a large and growing collection of test data.

The NVIDIA Solution – NHTSA Safety Element

OBJECT AND EVENT DETECTION AND RESPONSE

Object and event detection and response refer to the detection of any circumstance that's relevant to the immediate driving task, and the appropriate driver or system response to this circumstance. The NVIDIA DRIVE AV module is responsible for detecting and responding to environmental stimuli, both on and off the road. The NVIDIA DRIVE IX module helps monitor the driver and take mitigation actions when they're required.



HARDWARE

The core of the NVIDIA DRIVE AGX hardware architecture is NVIDIA Xavier, the world's first autonomous driving processor and the most complex SoC ever created. Its safety architecture was developed over several years by more than 300 architects, designers, and safety experts based on analysis of more than 150 safety-related modules. In combination with the proper Main Control Unit, it also supports ASIL-D, the highest functional safety rating.

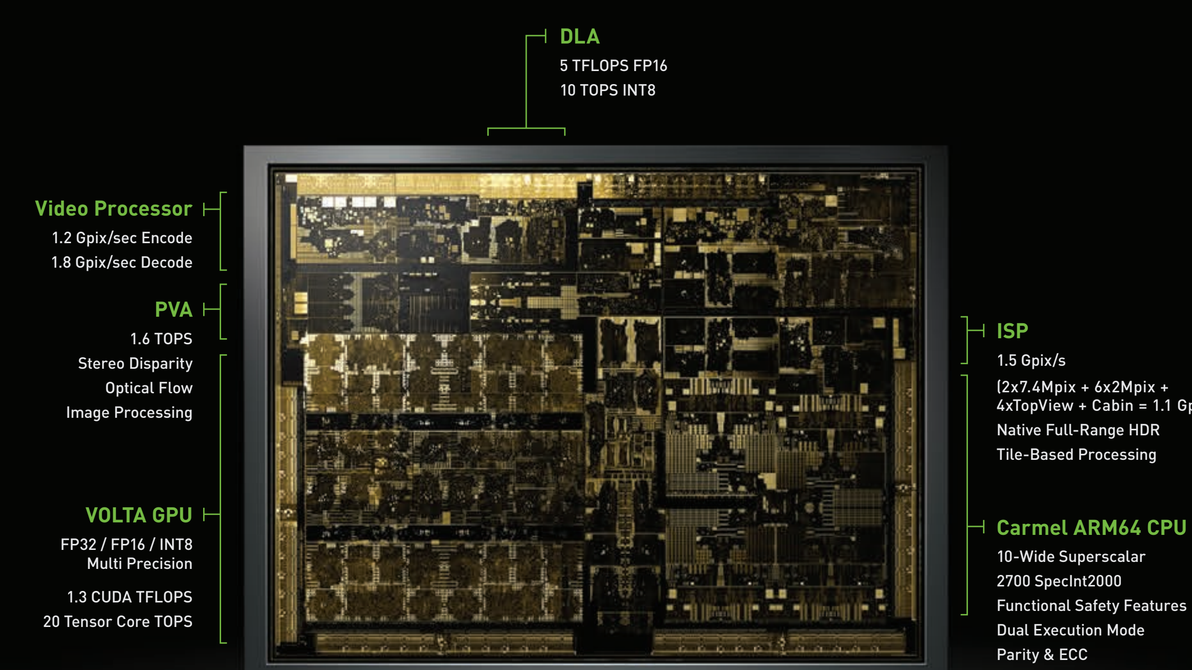
Xavier's 9 billion transistors give it the ability to process incredible amounts of data. A GMSL (gigabit multimedia serial link) high-speed input/output connects Xavier to the largest array of lidar, radar, and camera sensors of any chip ever built.

Six types of processors work together inside Xavier: an image signal processor, a video processing unit, a programmable vision accelerator, a deep learning accelerator, a CUDA GPU, and a CPU. Together, they process nearly 40 trillion operations per second; 30 trillion operations are for deep learning alone.

Xavier includes many types of hardware diagnostics. Key areas of logic are duplicated and tested in parallel using lockstep comparators and error-correcting codes on memories to detect faults and improve availability. A unique built-in self-test helps to find faults in the diagnostics, wherever they may be on the chip.

NVIDIA DRIVE XAVIER

THE WORLD'S FIRST AUTONOMOUS MACHINE PROCESSOR



SOFTWARE

The NVIDIA DRIVE AV software stack consists of three major software modules. **Perception** takes sensor data and uses a combination of deep learning and traditional computer vision to determine an understanding of the vehicle's environment, referred to as the World Model. Once the environment is understood, the **Planning** module uses this information to determine and score a set of trajectories and determine the best route. The **Vehicle Dynamics Control** module can then transform the chosen path into vehicle actuation.

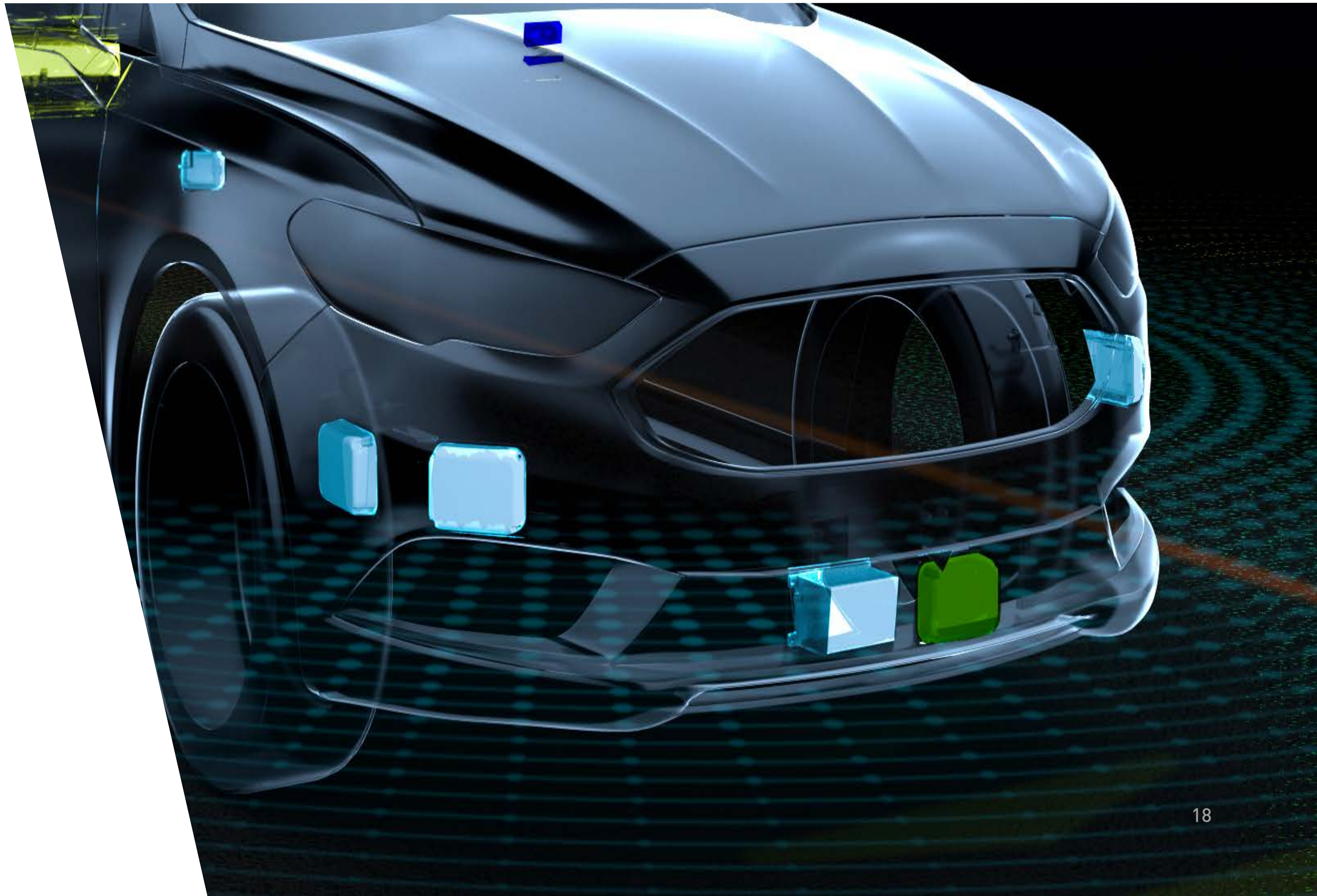
DRIVE AV currently uses more than 10 DNN models running simultaneously, in addition to a large suite of computer vision and robotics algorithms. However, the number of DNNs and the capabilities they cover is continually growing. For example, a dedicated DNN controls the detection and response to pedestrians and cyclists around the vehicle, running simultaneously with a DNN dedicated to traffic lights. We also expand the use of our DNNs to support features like automatic emergency steering and autonomous emergency braking, providing redundancy to these functionalities[10].

DRIVE Software Architecture.

Each major function, such as sensor processing, AI-based perception, localization, trajectory planning, and mapping is performed with multiple redundant and diverse methods to achieve highest level of safety. For example, DRIVE AV uses embedded modules for detecting and handling obstacles and drivable space. For wait conditions, we detect traffic lights, stop signs, intersections, and stop lines. For paths, we detect lane edges and drivable paths. This detection is happening over multiple frames, and objects are tracked over time. We also layer diversity by using multiple sensor types (radar, camera, and lidar). The triple combination of diverse DNNs, tracking of objects over multiple frames, and presence of different sensor types ensures safe operation within the operational design domain. Additionally, the integrated functional safety mechanisms enable safe operation in the event of a system fault.

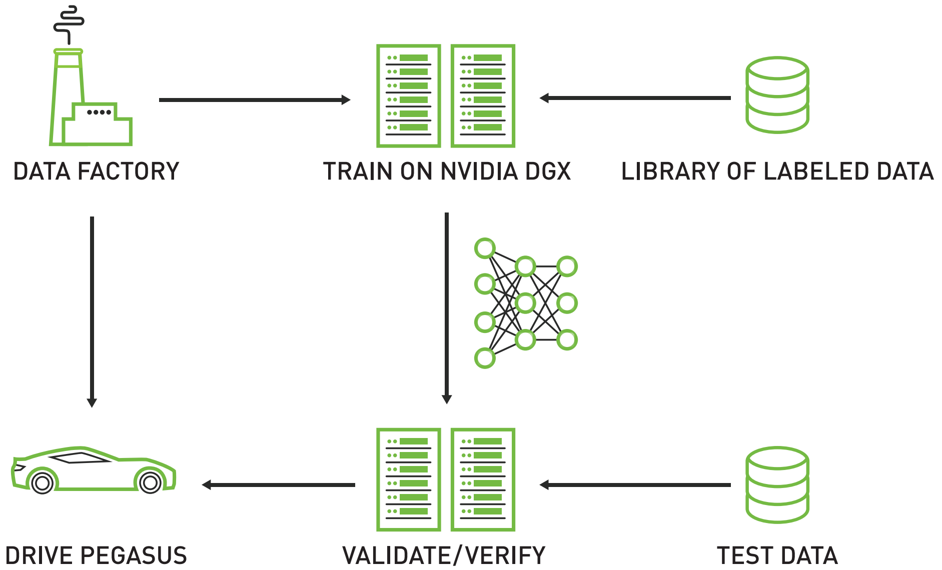
SENSORS

The first step in developing vehicle autonomy is data collection, which requires auto-grade sensors. The NVIDIA DRIVE Hyperion™ Development Kit enables self-driving development, data campaign processing, verification, validation, and ground-truth data collection for all automation levels.



DATA CENTER

After collecting sensor data, we process it and, in the case of camera data, select images to be labeled for training the AI. The whole process is continuously validated. We label not only objects and images within captured frames, but also scenarios and conditions in video sequences. The more diverse and unbiased data we have, the safer the DNNs become. We also define key performance metrics to measure the collected data quality and add synthetic data into our training datasets. The ultimate goal is to continuously add training data to build a comprehensive matrix of locations, conditions, and scenarios. Performance of neural network models is validated against the data and retested as new data is collected.



Training and Testing the Neural Networks.

In addition to labeling the objects in an image, we label the conditions under which data was collected. This provides a matrix of conditions we can use as a training dataset to test the performance of our DNN models against a wide range of scenarios. When performance doesn't meet key indicators, we collect and process more data for validation.

GPUs in the data center are used extensively to investigate new DNNs with diverse datasets, continually train neural network models, analyze the results of workflows, and test and validate outcomes using a large-scale systems for simulation in virtual worlds and re-simulation of collected data.

MAPPING

A robust mapping and localization process allows a self-driving vehicle to localize itself with precision, discern potential hazards, and then determine exactly where it can safely drive. NVIDIA DRIVE enables vehicle manufacturers to use maps from various global providers while also allowing the vehicle to build and update a map using sensors available on the car. We localize the vehicle to high-definition maps of every traditional map provider and perform exhaustive simulations to build in proper functional safety.

Our system-level monitoring processes continually diagnose and prevent faults and mitigate the effects of malfunctions and failures. For example, to ensure that a map is always available, the NVIDIA DRIVE platform allows them to be updated in multiple ways and assures that one instance of a map can replace another in the event of failure.

NVIDIA collaborates with mapping companies all over the world, including HERE, TomTom, Baidu, NavInfo, AutoNavi, ZENRIN, South Korean Telecom Co., KingWayTek, and many startups. Our application programming interface allows NVIDIA systems to communicate and calibrate our high-precision localization system with their high-definition maps.

SIMULATION

Occurrences of dangerous incidents experienced by a single test vehicle are extremely rare, making it hard to accurately assess safety or compare different designs[11]. For example, U.S. drivers experience a police-reported collision approximately once every 500,000 miles. To demonstrate that a self-driving system has a lower collision rate than human drivers requires a sizable test fleet driving many miles. As a result, it's very difficult to verify and validate vehicle self-driving capabilities solely using on-road testing.

DRIVE Constellation bridges this verification and validation gap. It's designed for maximum flexibility, throughput, and risk elimination and relies on high-fidelity simulation. It also uses the computing horsepower of two different servers to deliver a cloud-based computing platform capable of generating billions of virtual miles of autonomous vehicle testing.

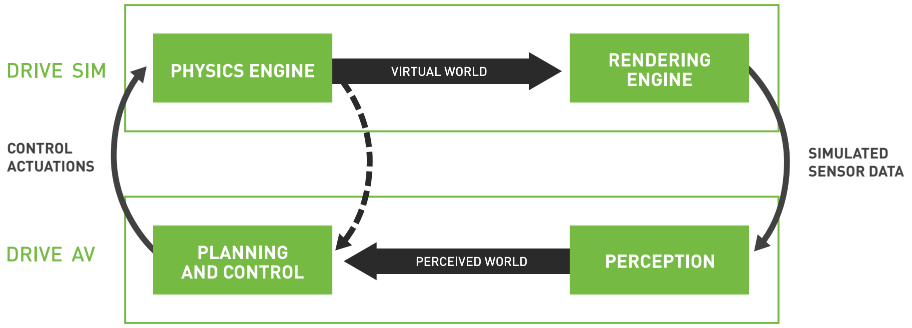
In the image above, the first server in DRIVE Constellation runs DRIVE Sim

NVIDIA DRIVE Constellation Servers Enable Hardware-in-the-Loop Testing.

software to simulate the multiple sensors of a self-driving vehicle and vehicle dynamics. Powerful GPUs accurately render sensor data streams that represent a wide range of environments and scenarios. This allows engineers to test rare conditions, such as rainstorms, snowstorms, or sharp glare at different times of the day and night. Each scenario can be tested repeatedly, adjusting multiple variables such as road surfaces and surroundings, weather conditions, other traffic, and time of day.

The second server contains a DRIVE AGX Pegasus vehicle computer that runs the complete, unmodified binary autonomous vehicle software stack (DRIVE AV) that operates inside an autonomous vehicle. It processes the simulated data as if it were coming from the sensors of a vehicle actually driving on the road, and sends actuation commands back to the simulator.

Together, these servers enable "hardware-in-the-loop" testing and validation.



DRIVE AV and DRIVE Sim Interaction.

RE-SIMULATION

In addition to simulation, NVIDIA uses re-simulation—playing back previously recorded sensor data, rather than synthetic data, to test the driving software stack. For example, we incorporate actual sensor data from automatic emergency braking scenarios using re-simulation to help eliminate false positives.

\ A TECHNICAL PERSPECTIVE ON VALIDATION AND VERIFICATION SERVICES

DRIVE Sim is engineered for safety validation and is the centerpiece of NVIDIA's autonomous vehicle validation and verification methodology. It's used for testing vehicle software at all integration levels (units, integration, and system) and at all abstraction levels (model, software, and hardware-in-the-loop). It's comprised of all components of the self-driving vehicle experience, accounting for sensor data, pedestrians, drivers, roads, signs, vehicle dynamics, etc.

To help this methodology more extensively explore the autonomous vehicle behavior, DRIVE Sim is adding support for taking snapshots (or checkpoints) and backtracking to restore a saved simulation state. At this point, simulation objects and their attributes can be mutated, allowing the study of variability around known driving scenarios.

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DATA RECORDING

Instead of synthetic data, NVIDIA re-simulation enables real data from sensors placed on test vehicles that are driving on the public roads to be fed into the simulation. To maximize the safety of self-driving vehicles, NVIDIA offers a combination of simulated data to test dangerous road scenarios coupled with real-world data from re-simulation.

ON-ROAD TESTING

NVIDIA created the DRIVE Road Test Operating Handbook to ensure a safe, standardized on-road testing process. This document specifies what must be done before, during, and upon completion of every road test. As recommended in the most recent U.S. DOT report *Preparing for the Future of Transportation: Automated Vehicles 3.0*[12], NVIDIA's process is modeled on the FAA-certified Pilot's Operating Handbook that must be carried in-flight with every general aviation aircraft in the United States.

On-road testing is always performed with a highly trained safety driver continuously monitoring the vehicle's behavior and ready to immediately intervene when necessary. A co-pilot monitors the self-driving software—like checking that the objects detected by the car correspond to those viewed live—and that the vehicle's path is valid for current road conditions.

Prior to allowing software to be tested on-road, it's extensively tested using unit tests and system simulation. The diagram on page 25 explains what steps need to be taken before the autonomous vehicle is permitted to drive on public roads.

Human-machine interface and driver monitoring

Before widespread deployment of AVs becomes a reality, this technology can help make human drivers safer today. Incorporating AI into the vehicle cockpit can add a robust layer of safety, ensuring that drivers stay alert or taking action if they're not paying attention.

The DRIVE IX software stack lets vehicle manufacturers develop in-vehicle driver-monitoring AI in a variety of ways. Similar to the way deep-learning algorithms are trained on driving data to operate a vehicle, the algorithms built on DRIVE IX can be trained to identify certain behaviors and infer whenever needed. For example, tracking a driver's head and eyes lets the system understand when they're paying attention and blink frequency monitoring can assess drowsiness. Depending on a manufacturer's preferences, the system can alert the driver using audio, visual, or haptic warnings to return their focus to the road.

DRIVE IX can also monitor the environment outside the vehicle. If a driver is about to exit the vehicle without looking as a bicyclist approaches alongside, DRIVE IX can provide an alert or prevent the door from opening until the bicyclist has safely passed.

DRIVE IX extends AI capability to detect individual passengers in a vehicle and let riders use voice commands for actions like temperature control or rolling down a window. Passenger detection also enables DRIVE IX to alert the driver if a child or pet has been accidentally left in the back seat, addressing the NCAP requirement to detect a child present in the vehicle[13].

The platform is designed to be expandable with custom modules. Gesture, gaze, and eye openness detections are performed using DNNs that work with integrated third-party modules to predict emotion.

When passengers are able to see what the vehicle sees and understand how it reacts to traffic situations, they can be assured that the vehicle is acting safely. Manufacturers can achieve this vital communication from the car to the driver with comprehensive driving data displays enabled by DRIVE AR. This customizable visualization software stack can display information such as the vehicle's route, how the vehicle is perceiving its surroundings, and its intended actions. For example, displays in the dashboard and back seat screens can show a 360-degree view around the vehicle, noting objects such as other vehicles and pedestrians. If one of those pedestrians is about to cross the road, a message could communicate that the vehicle is slowing for the pedestrian. These displays can also be interactive, allowing riders to toggle between screens showing points of interest, entertainment, or other route information.

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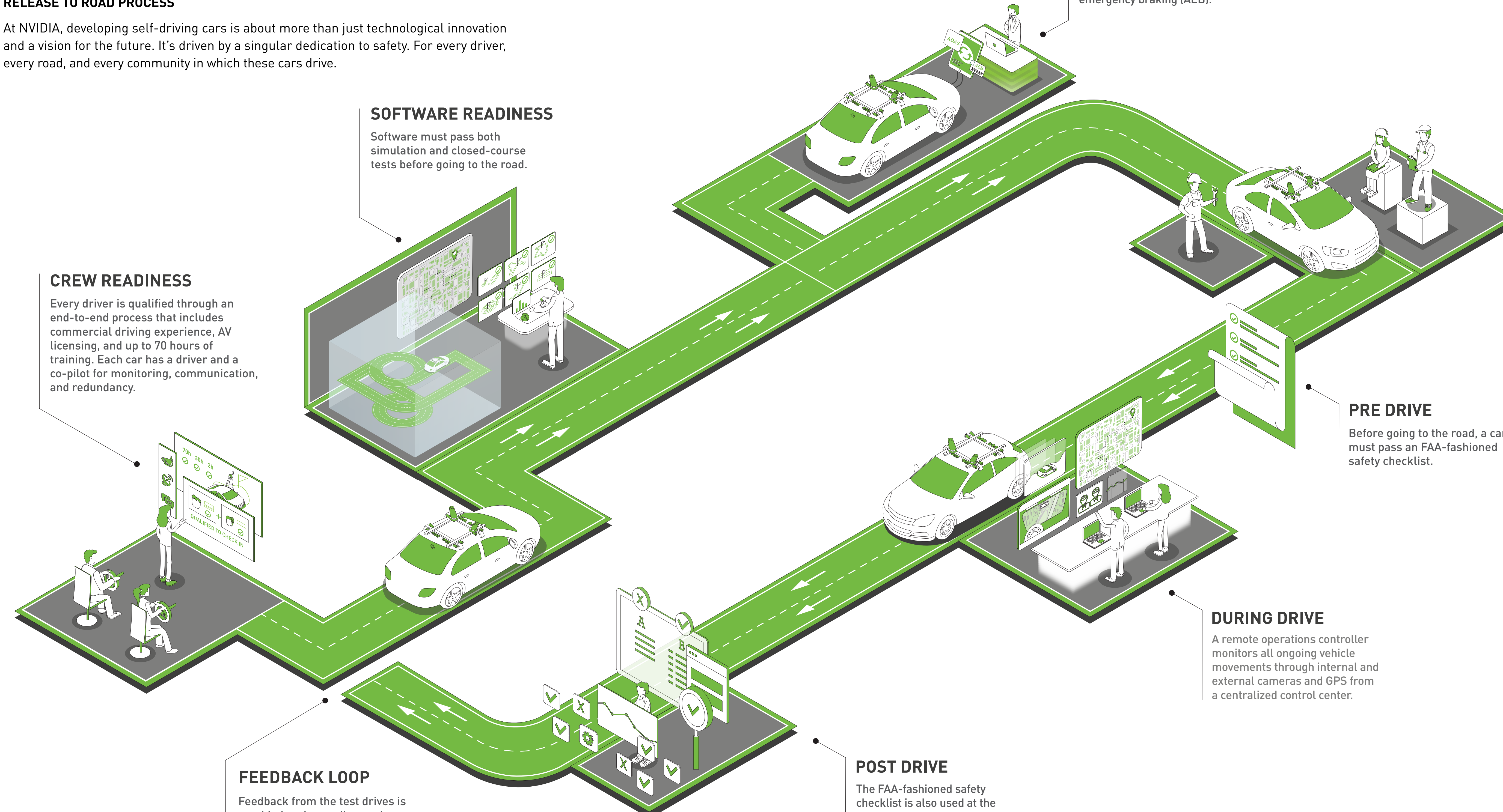
HUMAN-MACHINE INTERFACE

DRIVE IX and DRIVE AR enable driver monitoring and a passenger information system to assess driver awareness and perform the full driving or riding task.

THE DRIVE FOR AUTONOMOUS VEHICLE SAFETY

RELEASE TO ROAD PROCESS

At NVIDIA, developing self-driving cars is about more than just technological innovation and a vision for the future. It's driven by a singular dedication to safety. For every driver, every road, and every community in which these cars drive.



CREW READINESS

Every driver is qualified through an end-to-end process that includes commercial driving experience, AV licensing, and up to 70 hours of training. Each car has a driver and a co-pilot for monitoring, communication, and redundancy.

SOFTWARE READINESS

Software must pass both simulation and closed-course tests before going to the road.

VEHICLE READINESS

Every car has a five-star safety rating, ADAS capabilities, and sensors used for automatic emergency braking (AEB).

PRE DRIVE

Before going to the road, a car must pass an FAA-fashioned safety checklist.

DURING DRIVE

A remote operations controller monitors all ongoing vehicle movements through internal and external cameras and GPS from a centralized control center.

POST DRIVE

The FAA-fashioned safety checklist is also used at the conclusion of every trip.

FEEDBACK LOOP

Feedback from the test drives is provided to the readiness phases to help improve crew, software, and vehicle performance in the next trip.

CYBERSECURITY

An autonomous vehicle platform can't be considered safe without cybersecurity. Security breaches can compromise a system's ability to deliver on fundamental safety goals. To deliver a best-in-class automotive security platform with high consumer confidence, we've built a world-class security team and aligned with government and international standards and regulations. We've also built strong partner relationships to remediate security incidents and serve as a good steward in protecting customer data privacy.

NVIDIA follows international and national standards for hardware and software implementations of security functionality, including cryptographic principles. Plus, we adhere to standards set by the National Institute of Standards and Technology[14] and General Data Protection Regulations[15] to protect the data and privacy of all individuals.

We implement and advance cybersecurity guidelines, standards, and industry practices. Our cybersecurity team works with the Automotive Information Sharing and Analysis Center (Auto-ISAC), NHTSA, SAE, and the Bureau of Industry and Security (Department of Commerce). We contribute to Automatic Identification System (Department of Homeland Security), Federal Information Processing Standards (Federal Information Security Management Act), and Common Criteria standards or specifications. In addition, we use the SAE J3061 cybersecurity process as a guiding principle and leverage processes and practices from other cybersecurity-sensitive industries. We also participate in the SAE J3101 standard development, which ensures the necessary building blocks for cybersecurity are implemented at the hardware chip level. And we review platform code for security conformance and use static and dynamic code analysis techniques.

NVIDIA employs a rigorous security development lifecycle into our system design and hazard analysis processes, including threat models that cover the entire autonomous driving system—hardware, software, manufacturing, and IT infrastructure. The NVIDIA DRIVE platform has multiple layers of defense that provide resiliency against a sustained attack.

NVIDIA also maintains a dedicated Product Security Incident Response Team that manages, investigates, and coordinates security vulnerability information internally and with our partners. This allows us to contain and remediate any immediate threats while openly working with our partners to recover from security incidents.

Finally, as vehicle systems have a longer in-use lifespan than many other types of computing systems, we use advanced machine learning techniques to detect anomalies in the vehicle communications and behaviors and provide additional monitoring capabilities for zero-day attacks.

DEVELOPER TRAINING AND EDUCATION

NVIDIA is committed to making AI education easily accessible, helping both experts and students to learn more about these breakthrough technologies. The NVIDIA Deep Learning Institute offers multiple courses on how to design, train, and deploy DNNs for autonomous vehicles, and we produce a wide range of content to answer common questions on AI in the vehicle. We now have 1 million registered developers in eight different domains, such as deep learning, accelerated computing, autonomous machines, and self-driving cars.

To expand our knowledge and research the safety aspects of AI, we observe the DARPA Explainable AI (XAI) and participate in a series of DARPA Principal Investigators Workshops. We also engage with autonomous-driving researchers all around the world (for example, University of California Berkeley DeepDrive and Carnegie Mellon University in Pittsburgh).

\ The NVIDIA Solution – NHTSA Safety Element
VEHICLE CYBERSECURITY

NVIDIA implements foundational best practices in multiple cybersecurity actions and processes.

\ The NVIDIA Solution – NHTSA Safety Element
CONSUMER EDUCATION AND TRAINING

We continually develop, document, and maintain material to educate our employees, suppliers, customers, and end consumers. We offer multiple AI courses under our Deep Learning Institute and we report about new knowledge and developments. We also collaborate with the research organizations to invent improved approaches to autonomy and maintain the highest integrity level to co-create world-class thought leadership in the autonomous vehicle domain.

\ The NVIDIA Solution – NHTSA Safety Element
FEDERAL, STATE, AND LOCAL LAW

We operate under the principle that safety is the first priority. We comply with international, federal, state, and local regulations, and all safety and functional safety standards. We also frequently communicate with regulators to ensure that our technology exceeds all safety standards and expectations. We are active in standardization organizations to advance the future of autonomous driving.

\ NVIDIA ACTIVITY IN EXPERT GROUPS

NVIDIA is respected as an organization of experts in selected fields. Some of the working groups benefiting from our expertise include:

- ISO TC 22/SC 32/WG 8, "Functional Safety," international level
  - U.S. working group chairman
  - ISO 26262 Part 10 leader
  - ISO/PAS 19451 project leader
  - 2 of 7 U.S. delegates in international working group
  - U.S. leader for ISO 26262 Part 5, hardware development
- Euro NCAP technical expert through the European Association of Automotive Suppliers (Comité de Liaison de la Construction d'Equipements et de Pièces d'Automobiles)
- SAE Automotive Functional Safety Committee
- Multiple worldwide R&D consortia, technical review committees, and R&D chair roles

SUMMARY

NVIDIA is uniquely qualified to provide the underpinning technologies for the design, development, and manufacture of safe, reliable autonomous vehicles. Our ability to combine the power of visual and high-performance computing with artificial intelligence makes us an invaluable partner to vehicle manufacturers and transportation companies around the world.

We adhere to the industry's most rigorous safety standards in the design and implementation of the powerful NVIDIA DRIVE platform, and we collaborate with industry experts to address current and future safety issues. Our platform aligns with and supports the safety goals of the major autonomous vehicle manufacturers and robotaxi companies.

Building safe autonomous vehicle technology is one of the largest, most complex endeavors our company has ever undertaken. We've invested billions of dollars in research and development, and many thousands of engineers throughout the company are dedicated to this goal. During the past four years, more than 28,000 engineer-years have been invested in the hardware and software integrated in the NVIDIA DRIVE platform. There are currently more than 60 AV companies who have nearly 1,500 test vehicles on the road powered by NVIDIA technology. They recognize that greater compute in the vehicle enables redundant and diverse software algorithms to deliver increased safety on the road.

Safety is the focus at every step—from designing to testing and, ultimately, deploying a self-driving vehicle on the road.

We fundamentally believe that self-driving vehicles will bring transformative benefits to society. By eventually removing human error from the driving equation, we can prevent the vast majority of accidents and minimize the impact of those that do occur. We can also increase roadway efficiencies and curtail vehicle emissions. Finally, those that may not have the ability to drive a car will gain the freedom of mobility when they can easily summon a self-driving vehicle.

The autonomous vehicle industry is still young, but it's maturing quickly. NVIDIA holds a key role in the development of AVs that will revolutionize the transportation industry over the next several decades. Nothing is more exciting to us than overcoming technology challenges and making people's lives better. We invite you to join us on this ride of a lifetime.

APPENDICES

ACRONYMS

ASIL	Automotive Safety Integrity Level
CUDA	Compute Unified Device Architecture
DFA	Dependent Failure Analysis
DNN	Deep Neural Network
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Analysis
HMI	Human-Machine Interface
MISRA	The Motor Industry Software Reliability Association
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
PLC	Product Life Cycle
SAE	Society of Automotive Engineers
SOTIF	Safety of the Intended Functionality
V&V	Verification and Validation

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