



U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**



DOT HS 812 708

April 2019

An Assessment Method for Automotive Intrusion Detection System Performance

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Suggest APA Format Citation;

Stachowski, S., Gaynier, R., & LeBlanc, D. J. (2019, April). *An assessment method for automotive intrusion detection system performance* (Report No. DOT HS 812 708). Washington, DC: National Highway Traffic Safety Administration.

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> <i>OMB No.0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 2019		3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE An Assessment Method for Automotive Intrusion Detection System Performance			5. FUNDING NUMBERS DTNH22-14-D-00329L/0001 Task Order 0001	
6. AUTHORS Stephen Stachowski, Ron Gaynier, David J. LeBlanc, all UMTRI				
7. PERFORMING ORGANIZATION NAME AND ADDRESS University of Michigan Transportation Research Institute 2901 Baxter Rd. Ann Arbor, MI 48109			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Highway Traffic Safety Administration 1200 New Jersey Avenue SE Washington, DC 20590			10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT HS 812 708	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the National Technical Information Service, www.ntis.gov .			12b. DISTRIBUTION CODE	
13. ABSTRACT In response to the increased attack surfaces on modern vehicles due to expanded use of software and the introduction of wireless interfaces, a new market has emerged for intrusion detection systems (IDSs), which can detect some types of attacks and are under development by several companies. NHTSA requested development and demonstration of a method for assessing the in-vehicle performance of anomaly-based IDSs for vehicle data buses, specifically buses using controller area network protocols. IDSs may (1) protect vehicles from direct malicious manipulation of the data bus traffic, or (2) detect symptoms of unfriendly modification of firmware on one of the dozens of electronic control units (ECUs) on a modern vehicle's network. The methodology used provides a means to assess the performance of automotive IDS products, to provide quantitative and qualitative analysis of performance, and to offer insights on potential IDS options.				
14. SUBJECT TERMS			15. NUMBER OF PAGES 58	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

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Glossary

Acronym	Definition	Acronym	Definition
ACC	adaptive cruise control	LDW	lane departure warning
ADAS	advanced driver assistance systems	LKA	lane Keeping assist
APIM	OEM - ECU acronym	LS-CAN	low-speed CAN bus
AWD	all-wheel drive	MIL	malfunction indicator lamp
BCM	body control module	MS-CAN	medium-speed CAN bus
CAN	controller area network	NHTSA	National Highway Traffic Safety Administration
CAPL	Vector Infomatik's - communication access programming language	OBD	on-board diagnostic
CPU	central processing unit	OEM	original equipment manufacturer
DAS	data acquisition systems	OTA	over-the-air
DBC	vehicle-specific CAN message database file	PAM	park assist module
DLC	data link connector	PCM	powertrain control module
DTC	Diagnostic Trouble Code	PCS	precollision system
ECBS	electronically controlled braking system	PM	prevention mitigation
ECU	electronic control unit	PRNDL	Park, Reverse, Neutral, Driver, Lo
EPAS	electric power assist steering	RAM	random access memory
EHPAS	electro-hydraulic power assist steering	ROC	receiver operating characteristics
ESC	electronic stability control (also known as ESP, DSC)	SAE	Society of Automotive Engineers
FCW	forward collision warning	SQL	Structured Query Language
FN	false negative	TC	traction control
FP	false positive	TN	true negative
FPR	false positive rate	TP	true positive
GUI	graphical user interface	TPR	true positive rate
HS-CAN	high-speed CAN bus	UDS	unified diagnostic services
HSM	hardware security module	UMTRI	University of Michigan Transportation Research Institute
HVAC	heating, ventilation, air conditioning	USDOT	United States Department of Transportation
IDS	intrusion detection system	V2I	vehicle-to-infrastructure
IoT	Internet of things	V2V	vehicle-to-vehicle
IP	Internet protocol		

1. Executive Summary

In response to the increased attack surfaces on modern vehicles due to expanded use of software and the introduction of wireless interfaces, a new market has emerged for intrusion detection products/systems, which can detect some types of attacks. IDSs are currently under development by several companies worldwide. The National Highway Traffic Safety Administration requested development and demonstration of a method for assessing the in-vehicle performance of anomaly-based IDSs for vehicle data buses, specifically buses using controller area network protocols. IDSs may become an effective tool in a multilayered cybersecurity strategy to: (1) protect vehicles from direct malicious manipulation of the data bus traffic, or (2) detection of symptoms of other compromises, such as an unfriendly modification of firmware on one of the dozens of electronic control units on a modern vehicle's network.

NHTSA's core project intentions are focused on creating a methodology for the assessment of the following available IDS solutions.

- Select available IDS suppliers that could meet specified criteria and integrate their solutions into three unique test vehicle platforms.
- Devise a test methodology (described in this document) and then execute formal vehicle-based IDS performance assessment tests founded on this methodology.
- Execute an IDS performance assessment that includes simulated attacks to vehicle network bus traffic (i.e., injected CAN bus anomalies). The test platform includes customized data logging to capture IDS performance for post-test analysis.
- Conduct a post-test analysis to create a set of performance metrics to quantify or tier competitive supplier results.

This methodology provides a means to assess the performance of automotive IDS products, to provide quantitative and qualitative analysis of performance, and to offer insights on potential IDS options.

2. Introduction

2.1 Project goals

With the cooperation of participating OEMs, IDS performance was assessed using real-world vehicles to further develop and fine-tune the assessment approach. In line with NHTSA's mission to use diverse research partners with market ready or near market ready products for the advancement of transportation safety, the research team subcontracted a third-party software developer to design purposeful and unique simulated data bus attacks developed for specific modern vehicle applications. The intent of this project is not to assess the level of cyber-robustness of a particular vehicle architecture as much as to identify way to assess the quality and effectiveness of IDS automotive solutions currently in the market place. Key steps of this project are:

1. Develop a methodology which illustrates an IDS performance assessment test process/procedure.
2. Utilize interested OEM stakeholder vehicles as rolling test beds for IDS performance assessments.
3. Develop simulated attacks (scripts that represent bus anomalies) to be injected directly onto the vehicle's CAN bus or buses via an on-board diagnostic (OBD-II) data link connector [3].¹ Although different types of attack vectors are realized, this project focuses on direct injection to achieve intermediate results of the IDS products. The intent is not to assess all threat vector types during this project.
4. Develop a method to put competing IDSs into tiers based on selected quantitative and qualitative metrics. Explicit and intentional IDS competitive ranking is not examined as part of this project.
5. Develop a method to classify competing IDS models.
6. Develop recommendations for future IDS performance assessment improvements/procedures.

2.2 Prior work

A variety of researchers have previously demonstrated cybersecurity attacks to current vehicles. These include demonstrated attacks via the OBD-II port that require local physical access [4-7] as well as remote wireless exploits [8, 9]. The attacks impact systems ranging from theft protection and comfort features to the cyber-physical, which could be safety related by design [4-9].

The existing published attacks can be classified in two stages.

1. *Stage 1: Compromising the periphery.* In the first stage, attackers compromise vehicle (ECUs such as the infotainment or telematics units. The attackers discover weaknesses in the implementation or in the design, such as software buffer overflows, poor random-number generators, implementation flaws in the MP3² codec or Bluetooth driver, or

¹ SAE J1962, Diagnostic Connector, defines the requirements of an OBD diagnostic connector used on vehicles (traditionally for light vehicles) as required by U.S. On-Board Diagnostic (OBD) regulations; see for example On-Board Diagnostic Regulations and Requirements: Questions and Answers, Environmental Protection Agency, Report No. EPA420-F-042, December 2003, at <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100LW9G.PDF?Dockey=P100LW9G.PDF>

² MP3 is an audio coding format for digital audio.

improper data encryption. The objective of the attackers is to gain access to the vehicle's CAN bus through existing network nodes (ECUs).

2. *Stage 2: Injecting CAN messages.* In the second stage, attackers inject CAN messages onto the CAN bus. These maliciously crafted CAN messages can modify the behavior of the vehicle. For instance, it is possible to falsify the instrument cluster displays (e.g., speed or gas gauge), modify heating, ventilation, and air conditioning settings, radio controls, accelerate or decelerate the vehicle, or deactivate brakes. In many cases, attackers simply send more forged CAN messages than a legitimate ECU, making other CAN receivers believe that the forged information is legitimate. While such attacks are easy to detect and more advanced attacks are conceivable, they are typically not necessary since current vehicles do not implement any intrusion detection mechanisms. If an attacker has physical access to the OBD-II port, attack stage 1 is null (not necessary) and only stage 2 is executed.

It is assumed that an attacker successfully executed stage 1 and already gained access to the vehicle CAN buses. Therefore, our test scope focuses on stage 2, achieved by simulating attacks through the injection of messages onto the CAN bus by directly connecting to the data bus. This still simulates the intermediate effects of many remote (wireless) attacks that use counterfeit messages in their overall attack strategy.

2.3 Scope of project

The scope of this project is research and development of a methodology to assess modern vehicle CAN-based anomaly detection systems. The overall structure of this project creates a framework demonstrating a process to assess IDS products for the automotive market place. Four main project phases were created to support scheduled deliverables which monitor and meet this framework. They include the following.

1. Market Analysis: A market survey and selection process to narrow down potential IDS suppliers
2. Test Environment, Development, and Validation Test: Vehicle instrumentation, IDS integration, and system demonstration to prepare the vehicle for assessment
3. Test Plan: Test plan development, including test methodology and test procedure development (iterative)
4. Testing and Analysis: Assessment of test results and report

This study did not assess the complexities of any IDS learning and vehicle installation specifications. All IDS solutions appear to employ some form of machine learning,³ policy-based,⁴ or signature-based⁵ detection solutions; however, actual solution details are proprietary meaning the details are known only to each system supplier. Installation of a system for test in a vehicle, whether a stand-alone module, part of a gateway, or embedded within an existing module was done by each specific vehicle manufacturer. Special project conditions include local³ detection of CAN bus intrusions, and this is the core feature tested in this assessment (i.e., to ensure no postprocessing of CAN data occurs in supplier logs). The ability to counter intrusions with

³ See Section 3.3.2.1

⁴ See Section 3.3.2.2

⁵ See Section 3.3.2.3

preventative mechanisms, and/or the ability to use a remote server to learn from attacks and update local policies, is beneficial and discussed.

Subsequently, a secondary objective of this assessment is to provide recommendations for integrating an IDS solution into next-generation vehicle architectures in terms of topology, connectivity, detection strategy (e.g., CAN anomaly detection versus host-based anomaly detection), and resources.

2.4 Participating IDS suppliers and OEMs (test vehicles)

NHTSA helped choose a limited but sufficient number of suppliers and vehicle architectures to conduct this project. The research team chose a sample of three well-qualified IDS suppliers for assessment and competitive observation (herein described as Supplier - A, B, C, respectively and in no specific order).

In terms of vehicles (i.e., CAN bus architectures used as rolling test beds), availability and the willingness of OEMs to participate were the determining factors in the number of vehicle architectures included in the study. The sample size eventually chosen was three (herein described as Vehicle - 1, 2, 3, respectively and in no specific order). The goal is not to attempt to assess as many vehicle architectures as possible in hopes of assessing a significant CAN bus population; it is rather to develop a framework/process for the assessment of vehicle-based IDS integrations.

2.5 Overview of document

This study for the automotive market established distinct project phases to effectively integrate, exercise, and assess performance of in-vehicle IDS solutions. Project deliverables are defined in the following sections:

- 1: Executive Summary: Preamble on NHTSA-sponsored cyber-automotive project
- 2: Introduction: Includes project goals, scope, and participating project partners
- 3: Anomaly Detection Systems: Includes vehicle data bus overview, IDS and CAN bus assumptions, types of IDSs, and metrics defined for IDS performance calculations.
- 4: Test Concept: Defines overview of product testing and supplier selection
- 5: Test Method: Illustrates the research and test methodology for assessing modern vehicle IDS solutions.
- 6: Data Analysis and Findings: Provides overview of each IDS supplier metrics findings and performance summaries.
- 7: Conclusion: Offers highlights of test data analysis and insight on what was learned
- 8: Appendices: Support material used in this research and report
- 9: References: Support literature on related topics
- Glossary: Definition of document acronyms

3. Anomaly Detection Systems

Many modern vehicle safety and non-safety system features are directly reliant upon intra-bus and multiple bus stability and reliability. Communication bus nuances can be an indication of several potential reliability issues with either network infrastructure, network ECU hardware and/or software, sensors, electrical interference, etc. Given the increased use of electrified systems on today's vehicles and the accessibility to these systems, a new area of potential exploitation must also be taken into consideration: The possibility for an adversary wishing to cause disruption or harm to a vehicle bus and/or its components. The ability to detect anomalous behavior on a modern vehicle data bus is one area of research that the auto industry is working aggressively to develop. These development efforts have led to the creation of vehicle intrusion detection products commonly known anomaly-based IDSs. IDSs typically reside on the vehicle data buses they are monitoring and are designed to detect anomalous bus messages (that deviate from predefined "normal" bus traffic).

Much of this attention and effort is currently in progress by modern vehicle OEMs, suppliers, academia, government, and other stakeholders. This research takes an initial step toward developing a method of assessing the performance of anomaly-based detection systems developed for modern vehicles.

3.1 Vehicle data bus - background

For this project, IDS performance assessments are to be conducted on modern vehicle data buses, specifically CAN buses, which are two-wire buses whose messages are discrete packets with headers (message identifiers) that identify the message and payload that are in small 8-byte units. CAN bus traffic is decentralized, with individual ECUs transmitting (broadcasting) messages based on their own clocks. Automotive CAN messages are predefined and transmitted one of two ways: based on events or at periodic rates. Messages with the lowest identifier (ID) number receive the highest bus priority and access (via bit-wise arbitration) for transmission. Messages are broadcast and are visible by all other ECUs on the bus. Each ECU receives messages that are useful for its function (based on message ID) and ignores the rest of the messages. There is no authentication protocol⁶ built into CAN, but a receiving module does acknowledge when a message is received by the transmitting module. CAN buses are quite robust, where OEM network engineers exhaustively design architectures to effectively manage CAN bus traffic, avoiding bandwidth issues or instability (with possible failure/delay to communicate). Message transmission rates are typically 1 to 100 Hz, depending on bus type and application. It is very common for today's vehicles to contain multiple CAN buses based on vehicle complexity and feature content. Refer to Figure 1 for a representation of a standard CAN message format with an 11-bit identifier (ID).

⁶ https://en.wikipedia.org/wiki/Authentication_protocol

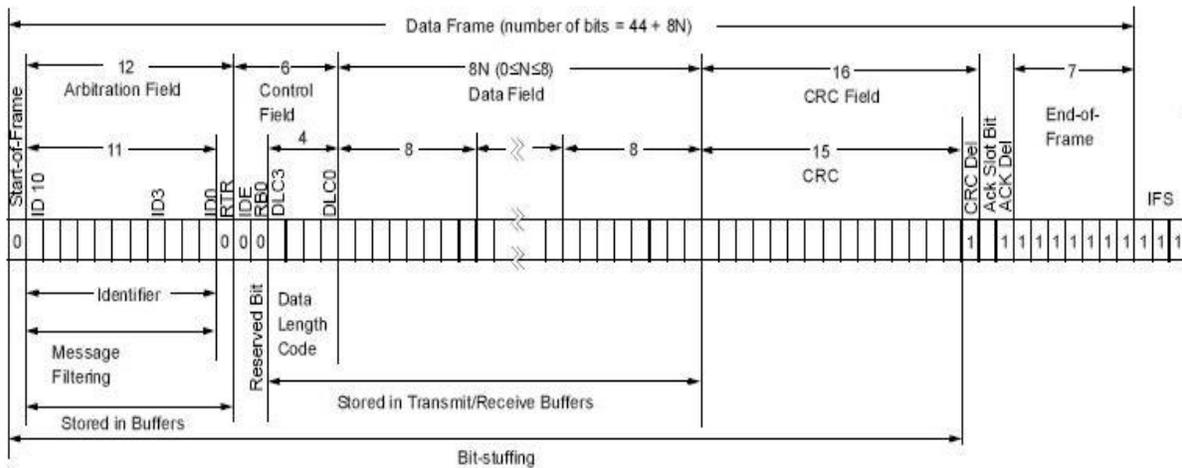


Figure 1: Standard CAN Frame With 11-Bit ID [10]

This project investigates and assess integrated IDSs applied to modern vehicle CAN bus networks only. Current production vehicles were used as assessment platforms to implement and assess these systems. The current state-of-the-art vehicle CAN buses used during this project do not incorporate any formal message authentication, security measures, or flexible data rate frame format and are comprised mostly of high-speed, medium-, and low-speed CAN bus topologies (based on the ISO 11898 standard) [11]. The anomaly detection systems tested for this project were specifically developed around specifications for simulated attacks to be injected onto high-speed (500kB) CAN bus applications.

Some supplier IDSs do include the ability to monitor other CAN bus types for anomaly detection if desired (e.g., medium- and low speed). There are many data bus network architectures on modern vehicles today. Architectures differ depending on OEM as well as vehicle model. Many OEMs strive to globalize some of their architectures to achieve cross-platform economies of scale and design robustness. Vehicle network segmentation is a balancing act based on bandwidth, safety, security, etc. Based on discussion, many OEMs are moving toward bus isolation/segmentation with multiple networks via the use of gateways. Figure 2 represents a simplified modern vehicle CAN bus architecture with a central gateway design. Note the central gateway model permits the ability to isolate the OBD-II bus segment (with physical connectivity) as well as the infotainment bus segment (with wireless connectivity) from the rest of the vehicle.

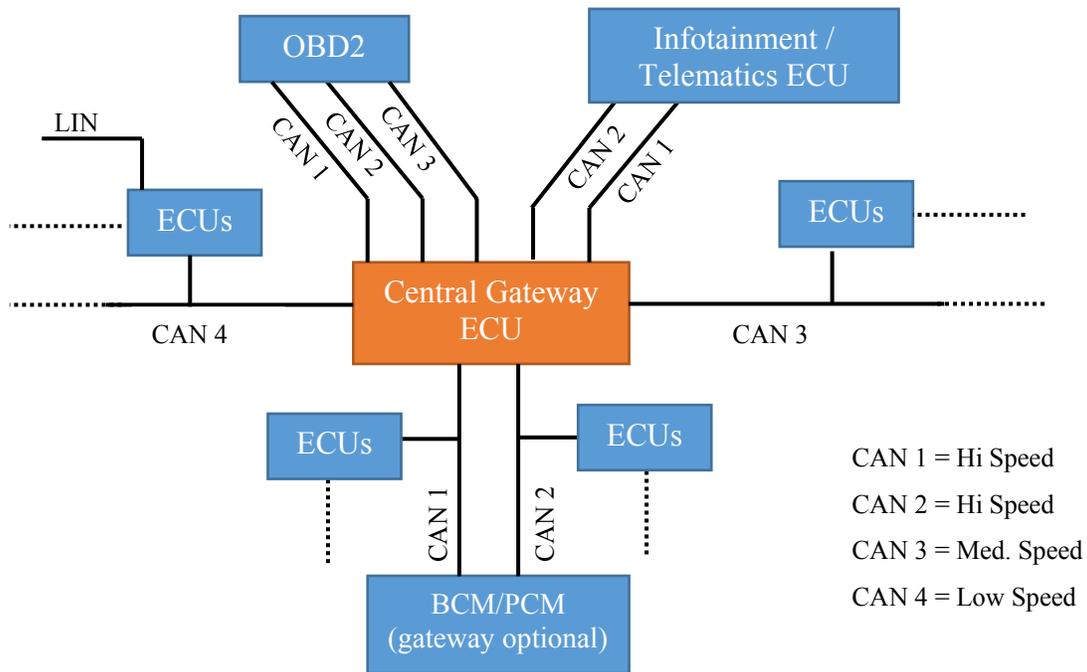


Figure 2: Simplified Modern Vehicle CAN Bus Architecture With Central Gateway

3.2 IDS/CAN bus assumptions:

IDS/CAN bus assumptions and directives regarding IDS product integration and CAN bus architectures were made.

- This project targets CAN bus protocols based on the ISO 11898 standard (i.e., it does not assess vehicle architectures using Secure CAN, CAN FD, FlexRay, or Ethernet).
- IDS products were required to detect and log vehicle data bus anomalies (with respect to “normal” bus traffic).
- Implied IDS detection philosophy: A significant goal for IDS suppliers is to achieve maximum sensitivity to anomaly detection (true positives) without compromising its ability to filter and correctly identify false alarms (false positives).
- IDS functional characteristics: Monitor-only mode then report (alert) user when an anomalous message is detected. The alert is recorded on a supplier log file (visual alert is optional via hardware or laptop).
- The CAN bus monitor/log equipment will output a periodic sync CAN message (0x7FA) on the main high-speed CAN bus only as a global timestamp used for post analytics. This sync message does not exist in any OEM CAN databases and does not impact vehicle functionality.
- IDS suppliers will provide an alert message (0x040) on the main high-speed CAN bus when an anomaly is detected for post analytics. This message does not exist in any OEM CAN database, and it does not impact vehicle functionality.
- Scripted simulated attacks are designed to represent a small subset of possible vehicle data bus anomalies.

- Vehicle CAN bus architecture types are not completely relevant to the assessment of IDS products; they offer a rolling test bed for IDS integration and a predefined message database from which to create scripted attacks.
- Simulated attacks are not intended to test vulnerability of the specific vehicle bus networks but are rather intended to exercise the IDS.
- IDSs are designed to interface to vehicle CAN bus networks only.
- IDS designs allow the flexibility to monitor any readily accessible CAN buses as needed for operation (at the discretion of the supplier).
- IDSs are designed to operate as a stand-alone independent node, physically connected to vehicle CAN buses via OBD-II connector.
- IDS are not hosted on any other vehicle ECU.
- Vehicle OBD-II connector limits IDS suppliers to CAN bus access types.
- IDS supplier data output is designed to represent a classic binary classification system.
 - When anomaly occurs - alert either as true positive - else false negative.
 - When no anomaly occurs - alert either as true negative - else false positive.
- IDS suppliers will provide assessment log files that will include index, local timestamp, CAN bus channel, anomaly CAN ID, anomaly data length, anomaly payload, anomaly type (optional), and count (optional).
- IDS physical integration locations are in-cab environments with easy access to driver for periodic operational checks.
- IDS project specification: Supplier systems are not to prevent or mitigate a detected anomalous message (some suppliers do offer this feature).
- IDS are tested independently (i.e., not batch-tested in parallel).
- IDS operation required only for two vehicle states: (1) engine off/accessory on or (2) engine on/accessory run state.
- IDS to be powered with vehicle 12V power source.

3.2.1 Terminology

In this report, an “anomaly” is any deviation in traffic on the vehicle data bus that is not consistent with an OEM design. An anomaly is activity on the data bus that is caused by a true malfunction or an intrusion by a third party that has caused illegitimate data bus messages or message behaviors. In this report, we are considering the message traffic itself, not subtle bus voltage variations that may be due to electrical failures, electromagnetic interference (noise), or mechanical bus failures induced by malicious parties. In addition, we are not assessing systems able to detect anomalous behavior on very subtle “fingerprints” of electrical characteristics (patterns) that can be associated with an individual transmitter of messages.

Note that vehicles often have myriad features with hundreds of signals being exchanged at rates of 100 Hz or more. There can be unusual traffic that is consistent with the vehicle design and benign from a security perspective, but this is rare due to the low use of a vehicle feature or a state that is encountered within the vehicle. An example might be almost simultaneous shifting into reverse and pressing the cruise control activation button. The vehicle designers structure the subsystem’s logic so that cruise control can only be activated in certain conditions, so this event will not cause any issues in the vehicle, yet it may be unusual. This event is neither an anomaly nor an intrusion.

Another term used throughout this document is “simulated attack,” which is the injection of data bus messages by the testing agency onto the data bus to simulate an intrusion. These simulated attacks are described in following sections; their purpose in the context of anomaly detection testing is to present the IDS with an “event” to assess the IDS’s response.

The ability to assess the capability of IDS anomaly detection is best described using a binary classification system, which essentially outputs a pass/fail score into two groups (an actual anomalous event occurs, or it doesn’t).

- 1) An anomalous event occurs and the IDS correctly determines that an anomaly has occurred (TP) or incorrectly indicates an anomaly has not occurred (FN).
- 2) No anomalous event occurs and the IDS correctly determines that an anomaly has not occurred (TN), or incorrectly indicates an anomaly has occurred (FP) results.

These binary descriptors will be utilized throughout this document to quantify the success or failure of IDS performance in various formats.

3.3 Types of IDS

In general, for a computer network that consists of two or more nodes, messages are generated at each node and flow between the nodes. The resulting network (bus) traffic forms a unique pattern of messages as a function of network operations. With respect to the automotive environment, especially modern vehicles, this bus traffic exists on data buses such as CAN buses between nodes (i.e., ECUs) as previously defined in section 3.1. OEMs construct bus traffic for a given set of use cases and operating conditions, regardless of vehicle operating state (whether static and dynamic), This is because of vehicle systems interactions, network design, vehicle make, model, and trim level content. “Bus traffic” is loosely termed and generally defines message content broadcast on the network between transmitters/receivers (ECUs). Bus traffic varies, both amount and type, at any given point in time based on vehicle operation. A vehicle and its associated network architecture is engineered to meet specific design specifications and operating conditions under which all bus traffic is deemed “normal” as developed by the OEM. Any unexpected or unknown CAN bus messages/data not expected or predefined by the OEM can be identified as an anomaly, which is why IDSs that focus on anomaly-based detections is examined during this project. Some types of anomaly-based IDSs are described in the following sections.

3.3.1 Detection versus mitigation:

IDS solutions for anomalous information detection and alerts are developed based on different design features and specifications. At the time of this project, automotive intrusion research and development is in the developmental/prototype phase. Many of the assessed intrusion detection products were designed to alert the vehicle operator upon detection of a bus anomaly and to define the type of intrusion (including acknowledgement of an anomaly detected for confirmation). The primary goal of this project is to establish a methodology to assess the performance of anomaly-based vehicle data bus intrusions. A key IDS specification stipulated is that upon detection of a bus anomaly the user is to be alerted via a log file entry, including visual indications on a laptop GUI for verification. IDS solutions with anomaly-mitigation features are also available for use in this marketplace but were not assessed as part of this project.

3.3.2 Detection design strategies:

IDS design strategies are proprietary, thus confidential, and vary among suppliers. These strategies, protected by corporate intellectual property, were not explicitly shared with the research team. However, it is assumed that the IDS products assessed on this project do incorporate one or more of the following design methodology and/or implementation strategies.

3.3.2.1 Machine learning

This approach is based on collecting statistically significant normal bus traffic (data) and building/categorizing models of what normal traffic represents. These models (profiles) are then compared with new bus traffic, and any deviation yields the possibility of anomalous behavior. In a sense, this constitutes pattern recognition and analysis that is categorized and used for future intrusion-detection assessment. One benefit to this approach is that it does not require prior knowledge of attacks and therefore can detect new attacks. A disadvantage to this approach is that the accuracy depends on the type and amount of normal bus traffic used to categorize the model. The baseline models established as normal require significant effort in data collection and interpretation techniques.

3.3.2.2 Anomaly-based (policy-based)

This approach is based on the ability to observe events or traffic on a bus and to apply a set of rules or boundaries that lead to a decision regarding whether a given pattern of activity (messages) is suspicious (anomalous). It is typical for a large database of rules to be generated via a training process that allows this type to be implemented. The paradigm is “anything that is abnormal is most likely suspicious.” This requires that a rules-based solution (model) be developed with training data based on normal traffic. The ability to define or estimate normal traffic can be labor intensive and timely for algorithm development (i.e., while creating a reference or baseline). One disadvantage of this approach is the tradeoff in the model design between not being able to identify when an attack has occurred (yielding a false negative) and falsely identifying an attack when one has not occurred (yielding a false positive). One benefit of this strategy is that it lends itself well to detecting new attacks without any prior knowledge.

3.3.2.3 Signature-based

This approach compares traffic or application data patterns of well-known attacks or weaknesses to current network traffic. If matched, then this accurately and efficiently detects an attack instance. This form of detection relies on prior information about types of attacks and doesn’t readily detect new attacks if not previously identified. However, this type of solution does provide a level of robustness to false positive events.

3.3.3 Implementation approach:

IDS implementation types are varied among suppliers and are based on design philosophies that can achieve optimal results. All IDS products assessed for this project were designed to be integrated into test vehicles as independent, non-cloud-based ECUs (simply as additional CAN bus nodes). The following list contains varied approaches to IDS implementation on light vehicles.

3.3.3.1 IDS node - non-gateway-based

The stand-alone implementation type, as used on this project, was accomplished via the ability to simply connect the IDS to the OBD-II connector for CAN bus access. To create a seamless and flexible test environment (between OEM test vehicles and IDS suppliers), the team disallowed physical modification to the vehicle data bus for IDS installation and operation. This “plug-and-play” type of integration indicates the IDS is not intentionally embedded between bus segments as

would be done in a ECU designed for a gateway application. In addition, there is no intentional data message translation or filtering between bus segments via the IDS module (as would be done by a gateway module).

3.3.3.2 IDS node - gateway-based

In many network architectures, especially those with multiple bus segments (subnetworks), gateways are used to isolate segments from one another. This provides an additional layer of security in the sense that bus messages cannot be transmitted from one segment to another without passing through a gateway which typically provides a whitelist/blacklist for message filtering. This feature is even more important with respect to isolating the vehicle from external threat vectors such as a wired OBD-II port or wireless communication channels (cellular, Wi-Fi, Bluetooth, etc.). In addition, gateways are now incorporating the ability to host any IDS software to not only filter but actively detect and identify anomalous bus behavior. The added benefit is that a gateway with IDS features offers the ability to monitor and protect all bus networks that the host is connected to. As previously indicated, this IDS implementation type was not utilized during this project.

3.3.3.3 IDS node – stand-alone (local) versus cloud-based

IDS product designs can take different physical forms and implementation types. In recent project assessments of real-time IDS products for the modern vehicle market, the research team has observed that these systems typically reside locally on the vehicle and are implemented as stand-alone modules, virtual machines, or can be hosted on existing vehicle ECUs (e.g., on a gateway). The benefits of local integration are decreased detection and response times to intrusions. Other IDS products associated with cloud-based solutions require a bus interface via some ECU, which then opens the potential benefits of big data analytics and software updates when a potential threat is detected. If cloud-based solutions are used to detect intrusions, the likelihood exists of increased detection and response times due to latencies communicating with cloud-based algorithms.

One potential benefit to cloud-based IDS is the ability to implement firmware locally (i.e., via an IDS ECU or host on an existing vehicle ECU) and offer the ability to update/improve its detection algorithm (remotely) based on fleet vehicle data threat analytics. This strategy offers the benefits of localized anomaly detection yet provides a connected means to upgrade IDS firmware on the vehicle with the latest detection algorithms available from the OEM/supplier.

This project assessed products performing real-time intrusion detection locally on stand-alone hardware. Similarly, these products were integrated into vehicles independently as add-on nodes on predefined bus segments and not hosted on any existing vehicle ECUs. Their designs did not include any cloud-based support features.

IDS implementation in modern vehicles continues to be an ongoing field of research. With it comes many discussions surrounding the benefits and limitations of this growing industry. The following topics relative to IDS integration on automobiles continue to be up for discussion in the automotive cyber community.

3.3.4 Implementation risk-benefit ratio

The benefits of anomalous (monitoring) type systems are:

- Ease of integration (IDS can simply be another stand-alone CAN bus node).
- Detection strategies may consist of a combination of heuristic analysis, machine learning, deep-packet inspection, and/or whitelist/blacklists.
- Deep packet inspection allows additional forensic fidelity of CAN messages' payload to that of a "predefined operating range."

- May include “active mitigation” strategies.
- Packaged/implemented in various formats: host-based IDS solution in a gateway, existing ECU, or stand-alone module.
- Can leverage cloud-based forensics (if designed)

The limitations of anomalous (monitoring) type systems:

- Require extensive learning phase for modelling/profiling “normal” and “non-normal” vehicle CAN bus profiles. The possibility of rare events could produce false positives and require updating/relearning if ECU updates affect CAN bus messages.
- Learning phase will be different for every vehicle model type (dependent on vehicle systems’ features).
- Rare events may only be contained via whitelist/blacklist as done in a filter-based solution.
- Proprietary IDS algorithms are defined by suppliers (quality/sensitivity of detection is supplier dependent).
- IDS algorithms themselves offer another mechanism by which software could be hacked and provide another portal to the vehicle data bus network.

3.4 Types of anomalies

As described previously in section 3.2.1, the term “simulated attack” is often used in the context of cybersecurity to define specific software (scripts) developed to output anomalous messages on the CAN bus. One of the research team’s roles was to develop a list of simulated attack types to help ensure IDSs are comprehensively assessed for each vehicle used on this project. Software developer Silent Cyber was subcontracted to independently create attack scripts for each test vehicle. Regarding attack script development, the following observations are important to consider:

- First, developing attacks for each vehicle may appear more as penetration testing of the vehicles and does not necessarily provide an adequate set of tests for the assessment of an anomaly-based intrusion detection system.
- Second, successful attacks are often very novel in their design, and if security experts could anticipate and create examples of all possible attacks, then they could certainly design safeguards against each.

Therefore, an investigation of categories of simulated attacks on the CAN bus that would manifest themselves as different from normal bus traffic (and hence considered anomalies) was undertaken and empirical tests that exercise IDS abilities to identify these CAN bus anomalies was designed. Conversely, the team also designed empirical vehicle test scenarios where the driver activated certain vehicle features (both usual and unusual) to determine if the IDS will incorrectly identify normal CAN bus messages as anomalous messages (i.e., false alerts).

The following is a summary of test anomaly types developed for this project:

3.4.1 Test IDS ability to recognize messages that deviate from the normal cyclic message rate.

Send anomaly messages faster than the cyclic rate for the equivalent normal messages. (Faster, rather than slower, messages tend to stress the system).

3.4.2 Test IDS ability to track messages that contain counters

Inject anomaly messages that contain bogus message counters. The count value in the anomaly messages is correct in sequence as determined by the count value of the last normal message transmitted on the bus. This results in the next normal message following the attack to appear out of sequence.

3.4.3 Test IDS ability to rationalize message content from system wide status

Inject anomalous messages that contradict current vehicle status (command on the malfunction indicator lamp when no diagnostic trouble codes are set, send diagnostic requests when inappropriate to vehicle operating condition, request more torque when brakes are applied, etc.).

3.4.4 Test IDS ability to detect violations of BUS OFF timer

Use the Vector Informatics' CANStress tool to cause a controller into enter a BUS OFF state by corrupting the controller's messages and sending "evil twin" anomalous messages during the BUS OFF timeout period (~1 sec). This type of attack was proposed but not successfully implemented on this project.

3.4.5 Test IDS ability to distinguish anomalous messages from similar messages (invoked by normal driver/vehicle behavior) - false positive tests

Conduct normal driver use-case scenarios to elicit false positive alerts. The intent is to have the driver exercise the vehicle under typical vehicle operating conditions to invoke CAN bus messages which correspond to similarly injected anomalies. For example, if an injected anomaly (attack) consists of changing transmission status to Reverse (while the vehicle is in Park), the corresponding false positive use-case would be that the driver physically shifts the vehicle from Park to Reverse. The intent is to test if the IDS can distinguish between valid and invalid bus content within a given vehicle state/context.

3.4.6 Test IDS ability to distinguish anomalous messages from unusual but normal bus behavior (invoked by non-normal driver/vehicle behavior) – false positive tests

Conduct non-normal driver use-case scenarios to elicit false positive alerts. Driver exercises vehicle under "unusual" operating conditions or at "unusual" times to determine if the IDS generates false positives. For example, on a vehicle with push-button PRNDL, where a driver can press all buttons at once, or pressing "R" while at highway speeds in Drive. The intent is to test if the IDS can distinguish between valid and invalid bus content within a given vehicle state/context.

3.5 IDS performance measures

One of the primary goals of this project is to demonstrate a methodology to assess modern vehicle integrated IDS solution performance. To do so requires establishing a framework with the ability to classify, test, and tier IDS solutions for detection accuracy. The binary classification system lends itself well to achieving this goal. A secondary goal of this project is to assess IDS solutions based on qualitative and subjective attributes that will augment objective results.

A summary of the final metrics used for the internal assessments are shown in Table 1.

Table 1: Metrics Summary

	Metric	Description	Rational
1	False Negative Rate	How often the supplier failed to identify an attack	Base metric, necessary to calculate most other metrics
2	False Positive Rate	How often the supplier identified an attack when none was occurring	Base metric, necessary to calculate most other metrics
3	True Positive Rate (Recall)	What fraction of the total actual attacks the supplier caught	Useful for determining detection rate of real attacks
4	Precision	What fraction of identified attacks were true attacks.	Useful for determining accuracy—how often the supplier “cries wolf”
5	Informedness	Provides the probability of a correct classification given the entire data set.	What is the probably that the system is correct over all events?
6	Markedness	Provides a measure of confidence in the classification relative to the subset of classifications within the data set.	What is the confidence that a subset of classified events (e.g., Positive classifications) is correct?
7	F1 Score	Varies depending on β value chosen. Weighs precision against recall based on selecting which is more important.	Useful for compressing precision/recall down into one number that reflects our perceived importance of both
8*	Latency to filter benign messages	How long it takes for CAN messages to pass through the supplier’s filter	If this number is too high, the IDS solution effectively becomes unusable
9*	Detection Speed	How long it takes the supplier to log an attack after it begins.	Makes collected attack data more useful, quicker detection speed makes prevention more likely to work

**NOTE: Summary metrics 8 and 9 were time-dependent variables and were expected to be incorporated into this project. However, as the assessment process transpired, these time-dependent metrics were not considered relevant at this stage of an IDS investigation, and any logging effort for these two metrics were put on hold. The IDS project investigation only includes metrics 1 through 7. It is conceivable that metrics 8 and 9 would be used in future assessments where all IDS have matured to embedded hardware solutions that are locally integrated onto a vehicle.*

It is reasonable to assume that each modern vehicle OEM is likely to have unique IDS goal preferences and selective weighting between these performance measures.

3.5.1 Binary classification of anomaly detection

An IDS is essentially a classic binary classification system as introduced in section 3.2.1. When given an input, the IDS will output one of two classifications: (1) an anomaly is detected or (2) no anomaly is detected. A positive event is when an attack (or simulated attack) is occurring. A negative event is all other moments, including times with unusual but benign bus traffic.

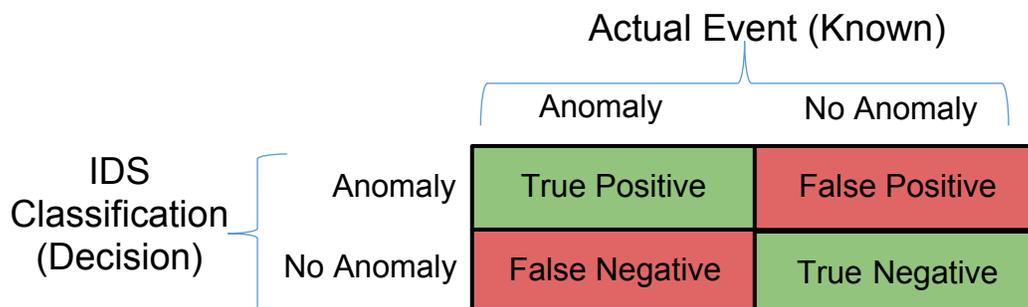


Figure 3: Binary Tests Classification

In Figure 3, the green squares are binary classifiers where the IDSs have made correct decisions - correctly identifying an attack is occurring (TP) or that an attack is not occurring (TN).

Conversely, the red squares are binary classifiers where the IDS have made erroneous decisions—that an attack is detected when none is occurring (Type I error: FP) or an attack is not being detected but is occurring (Type II error: FN).

Unlike false positives, false negatives can only occur when an anomaly occurs and the IDS fails to detect the event. If testing exposes different systems to the same number and type of anomalies, then a count of false negatives is a useful measure of performance.

As with any binary classification system, a ranking of performance between IDSs exposed to the same set of true events and false events requires the assessor to express the relative weight of detection rate (percent of events that are detected) versus the false positive rate (how many false positives). This weighting was intentionally not provided in this project and would typically be chosen by an OEM whose higher-level plans for using the information becomes important. For instance, if one OEM wishes to flag all true events and can tolerate false alerts, then suppliers would seek to meet those criteria. If another OEM needed to avoid false positives at all costs, the suppliers would tune their system differently.

3.6 Quantitative metrics

The ability to model and classify IDS performance is one of the key goals of this project. Using summary statistics on the binary classifiers as shown in Figure 3, one is then able to derive additional quantitative metrics (ratios) to help identify and tier supplier performance relative to an optimal standard.

3.6.1 Precision and recall

Precision and recall are often used in machine learning and binary classification problems like this project entails. Their formulas are as follows.

$$Precision = \frac{TP}{TP + FP}$$

$$Recall = \frac{TP}{TP + FN}$$

Precision is a measure of a classifier's ability to identify actual attacks from the total number of events that are examined. Identifying normal traffic as an attack (FP) will very quickly drive this number down. Note that this number does not consider missed attacks. A system that correctly detects a single attack and misses all others (large FN), while never falsely identifying normal traffic as an attack (where FP=0), will achieve very high precision but is not very useful.

To offset this shortcoming in precision, recall is used to measure how well the IDS caught all possible actual attacks. Any missed attack will quickly drive this number down. However, this metric does not account for labeling benign traffic as an attack (FP)—a system that always labels all traffic as an attack will achieve very high recall, but is also not very useful (and will have very low precision).

Precision penalizes false alarms whereas recall penalizes failing to correctly raise the alarm.

3.6.2 F-score

F-score is a combination of precision and recall; it compresses the pair of numbers down into one usable number and is a measure of a test's accuracy. The general equation for F-score is

$$F_{\beta} = (1 + \beta^2) \frac{Precision \cdot Recall}{(\beta^2 \cdot Precision) + Recall}$$

Where β is a tuning variable that weighs whether precision or recall is more important. For our calculations, we used a pair of β values. First, we set $\beta = 1$. This weighs precision and recall evenly. For our second metric, we set $\beta = 0.5$, which biases our F-score toward precision based on the assumption that all suppliers would do relatively well at detecting attacks but might differ in their ability to have low FP. Specifically, this makes precision twice as important as recall.

This measure has the advantage of being quick and easy to read. If the relative importance of precision and recall is determined ahead of time for each IDS tested, determining the best performer is just a matter of calculating the F-score and comparing the results.

Unfortunately, F-scores do not consider true negatives and, therefore, are not used as the sole metric for comparison.

3.6.3 Informedness and markedness

The last metrics assessed are informedness and markedness. Their formulas are as follows.

$$Informedness = \frac{TP}{TP + FN} + \frac{TN}{TN + FP} - 1$$

$$Markedness = \frac{TP}{TP+FP} + \frac{TN}{TN+FN} - 1$$

Informedness describes the correlation between the IDS's ability to predict the presence or absence of an attack and the total number of events. It is the ratio of properly classified attacks to the total number of actual attacks (referred to as sensitivity), plus the ratio of events properly classified as void of attacks to the total number of events void of attacks (referred to as specificity). Informedness values range from -1 to 1. A perfect system would have an informedness score of 1.

Markedness differs from informedness in that it calculates the ratio of properly classified attacks to the total number of events classified as attacks (positive predictive value) plus the ratio of events properly classified as void of attacks to the total number of events classified as void of attacks (negative predictive value). As with informedness, the values range from -1 to 1, and a perfect system would have a markedness score of 1.

These measures compensate for the bias inherent in both precision/recall and F-scale metrics. They should be robust to sample size differences but are more difficult to comprehend than the other metrics.

3.6.4 Response time

The IDS response time (detection speed) was not used during this project, but it can be a vital factor in higher resolution performance analysis of future generation IDS products as the technology evolves. Some key considerations about the impact of response time when considered relative to IDS performance:

- Latency to filter benign messages: This refers to the time delay of filtering valid messages that may be incorrectly categorized as anomalies. This may apply more directly to IDS applications that function with filtering capabilities (as seen on gateway ECUs). It is only reasonable that this characteristic is minimized for optimal bus performance.
- Detection speed: This metric identifies the time to read, validate, and send an alert (log, visual, etc.) that a message is categorized as an anomaly. It seems reasonable that normal messages are validated in a shorter amount of processing time than true anomalous messages. Minimum detection speed is desirable.
- Latency due to plausibility checks: To insure an IDS algorithm decision-making process is accurate requires validation and verification yielding plausibility checks for CAN messages. Doing so requires additional ECU processor clock cycles providing a measure of confidence in detection decisions. These "additional" cycles for decision filtering will most likely increase decision latency. The goal is to maximize IDS detection quality by minimizing improper message classification.

The importance of response time constrains the role that cloud components of an IDS can play. Cloud components refer to the possibility of using off-board computation and data sets to assist in the onboard (local) performance of IDS. Since response times should be on the order of less than a second, this prevents cloud components from being in the real-time decision path of an IDS; but they can serve other important roles, such as regional learning from fleets of vehicles and adjusting the filters, logic, or parameters used on board the vehicle by providing wireless information to the IDS.

3.7 Qualitative metrics

In addition to quantitative metrics previously described, a set of qualitative metrics considered for IDS supplier assessment and selection was applied. These metrics are

1. *Flexibility of solution*: How flexible is the IDS solution to account for a vehicle production line which includes many trim options for a given vehicle model? For instance, how flexible is it to account for many different electronics platforms, each of which offers thousands of slight variations (e.g., different equipment features and different software versions per ECU)? How well will the solution handle software updates of ECUs, replacement of ECUs, etc.?
2. *Forensics capabilities*: What features does the IDS solution offer to investigate anomalies? Are cloud-based services offered, and what features do they offer?
3. *Future proof*: Is the solution future-proof by being easily and regularly updateable? Does it allow updates to the IDS software and its configuration separately?
4. *Effort*: What effort is required to integrate the IDS solution in a vehicle, mainly cost. For instance, is a single centralized IDS implementation required or distributed throughout a vehicle (on various individual ECUs)?
5. *Performance*: Will the IDS solution run on a production grade automotive micro-controller, and what performance specifications does it have?

As stated above, qualitative assessment allowed the team the ability to guide the selection process for mature IDS supplier products and integration readiness. However, the research team supplier performance assessment focused on the testing and analysis with respect to quantitative metrics only.

4. Test Concept

4.1 Basic test concepts

As indicated early in this document the intent of this project is to test and assess in-vehicle IDS solutions by injecting simulated CAN bus attacks in the form of CAN message anomalies. These anomalies are designed to manipulate “normal” vehicle CAN messages by various formats as indicated in section 3.4. The intent is not to attack the vehicle per se, but to exercise the integrated in-vehicle IDS where the vehicle data bus architecture is used as a rolling test-bed.

Anomalies are injected directly onto the vehicle CAN bus through the OBD-II port on the main high-speed bus only. Vehicle actions taken during simulated attacks include both routine and unusual events. The emphasis is to conduct vehicle operations through naturalistic means with occasional operation that could be classified as fringe, yet normal.

To expose the IDS solutions to naturalistic vehicle operating conditions requires the ability to test for three sequence types:

1. **Stationary Test Sequence:** Initiate tests (simulated attacks) while the vehicle is stationary (engine on/transmission in park).
2. **In Motion Test Sequence:** Initiate tests (simulated attacks) while the vehicle is in motion (~25mph on straight-away).
3. **False Positive Testing:** In addition to monitoring for false positives for in motion and stationary test types, an extended duration drive (without simulated attacks) was conducted, during which vehicle features were exercised in a prescribed and naturalistic manner to elicit false positive alerts. (Note: this includes behaviors indicated in the false positive attack categories identified in sections 3.4.5 and 3.4.6).

In motion and stationary sequences differ slightly, but both utilize the many similar attack test types. The goal is to determine if the IDS is consistent in its detection capabilities under different vehicle operational states. The False Positive drive sequence is an attempt to determine if the IDS is prone to false positives under normal operating conditions.

During test development, an attempt was made to identify as many False Positive cases that correspond to attack test cases as possible. We defined a false positive case as an activation of a vehicle function that will invoke a CAN bus messages similar to an injected anomaly (e.g., if an injected anomaly message contains PRNDL misinformation, such as Reverse when in Park, then the false positive test type is to have the driver shift from Reverse to Park). By doing so, we can determine if the IDS can distinguish between valid and invalid bus content.

4.2 Vehicle considerations and vehicle selection

Considerations:

Throughout this report, three vehicle bus architectures become evident.

1. Current modern vehicle bus architectures, like those used during this project (as represented in Figure 4).

2. Vehicle architectures that include a security gateway. From a security standpoint on modern vehicles, it is becoming more apparent that a security gateway is a promising option to co-host the IDS in the future. Note that a security gateway provides basic filtering features to limit intrusions from external threat vectors such as OBD-II or infotainment sources and provides the ability to segment select buses from one another. The primary objective includes understanding how much additional value an IDS solution provides for intra-bus intrusion.
3. Proposed future architectures: Understanding how IDS solutions can support future architectures is the secondary objective.

Although not explicitly defined in Figure 4, OEMs typically include gateways in many of their network architectures, and it will be an attractive option to have IDS integrated onto a security gateway module. Gateways are currently used in production vehicles to segment CAN buses (e.g., OBD-II, infotainment, powertrain, body, occupant safety-critical, non-safety critical). Co-hosting the IDS in the security gateway is a logical approach. The gateway can enable filtering between network partitions based on preprogrammed or cloud-updated whitelists/blacklists, whereby the IDS could provide intra-bus detection.

Vehicle selection:

Test vehicle support was made possible by OEM stakeholders who expressed a willingness to participate in this project and was a direct factor in the number of unique vehicle architectures utilized. As previously indicated, the three vehicles chosen were anonymized as Vehicle 1, 2 and 3 respectively. The goal was not to assess as many vehicle architectures as possible in hopes of assessing a significant CAN bus population; but rather to be used as a guide to create a framework upon which to build a process for the assessment of IDSs.

Vehicles were purposely chosen to help achieve variability between OEMs as well as systems content (low- to high-feature content) to expose IDS suppliers to significantly different test beds (i.e., CAN bus architectures). The ambition was to provide a broad-based test environment for IDS performance assessments of modern vehicles.

Table 2 summarizes selected feature content of the test vehicles. Minor features are not included. Table 2 shows that Vehicle 1 had the most content, Vehicle 2 the least content, and Vehicle 3 moderate content.

The simulated attacks are different for each model and are influenced by the specific CAN bus message traffic and the vehicle features. Some vehicles, such as Vehicle 1 in this project, have many features such as crash avoidance systems, seat adjustment, and memory (cooled) front seats. More features translate into more data bus traffic, more combinations of data bus messaging, and more potential for unusual data bus traffic, such as when two infrequently-used features are exercised at the same time. Furthermore, the simulated attacks are customized for each vehicle so that there are notable effects of some of the simulated attack actions (e.g., an instrument cluster icon is activated).

Given that simulated attacks are different for each vehicle, it becomes less useful to compare the performance of an IDS across different vehicle models. That is, if the test depends on the feature content, then it stands to reason that comparing vehicle models, given IDS performance, is not meaningful.

Table 2: Vehicle feature content

	Vehicle 1	Vehicle 2	Vehicle 3
Vehicle type	5-door crossover	5-door Hatchback	2-door coupe
Model year	2016	2016	2015
Architecture topology	Multi-bus, multi-gateway	Multi-bus, multi-gateway	Multi-bus, multi-gateway
Feature content level	Most features	Fewest features	Many features
Gasoline engine	4-cylinder turbo	4-cylinder	8-cylinder
6-spd automatic transmission	Yes	Yes	Yes, with manual paddle
Drive wheels	All-wheel drive	Front-wheel drive	Rear-wheel drive
Climate control	Dual-zone electronic auto-climate control	Single-zone air-temp control	Dual-zone electronic auto-climate control
Heated front seats	Yes (and cooled)	Yes	Yes
Front seat position memory	10-way power, with driver memory	No, manual seats	2 memory power
Remote engine start	Yes	Yes	Yes
Power tilt/telescope steering column	Yes	No, manual seats	Yes
Remote keyless entry	Yes, with keypad	Yes	Yes
Power locks/windows	Yes	Yes	Yes
Dual power mirrors	Yes	Yes	Yes
Steering wheel controls	Yes	Limited	Yes
Reverse sensing	Yes, rear camera	No	Yes, rear camera
Navigation	Yes	Yes	Yes
Infotainment with Satellite radio	Yes	Yes	Yes
Other features	Blind spot information; cross traffic alert; active park assist; adaptive cruise control; forward crash avoidance; lane-keeping system	Non-applicable	Power sun roof; Stability traction control; variable assist steering

4.3 IDS supplier considerations and supplier selection

As previously indicated in section 2.4, three qualified suppliers were identified as participants to be assessed. The intent is not to grade or rank supplier performances per se, but to establish a methodology to assess a variety of competing anomaly detection products customized for modern vehicle automotive applications. Therefore, it was decided not to identify supplier company names. Again, suppliers are identified as Supplier A, B, and C respectively.

All project IDS suppliers provided a stand-alone (non-gateway) anomaly-based detection strategy as their design of choice. Their designs incorporated local detection of real-time anomalies and did not leverage any cloud-based support features. All supplier products were still considered in the developmental prototype design stage; however, each product used in this project included customized hardware utilizing embedded microprocessor-based architectures (i.e., no virtual machine solutions were selected for this project).

In support of test assessments, suppliers were required to physically integrate their products onto each test vehicle and then be assessed independently for performance. As requested by suppliers and agreed to by the team, the integration and calibration process essentially consisted of two development stages: (1) off-site predevelopment work and (2) on-site development and final product “training/calibration”.

5. Test Method

5.1 Test equipment including IDS

To physically conduct performance assessments of automotive IDS products required the research team to design a rolling vehicle test-bed to meet necessary data capture and logging specifications. Figure 4 depicts a high-level vehicle integration architecture with associated test equipment capable of performing such a task. This diagram illustrates both attack interface locations as well as data acquisition system monitoring locations for this test-bed.

The vehicle test-bed is used to inject simulated attacks via anomalous CAN messages as well as capture complete CAN bus logs. As described in section 3.4, the software developer provided an attack module (hardware/software attack scripts) with an intuitive user laptop interface to conduct all simulated attacks (true positive test cases). CAN bus data was captured via two methods: (1) data acquisition systems (DAS) log files and (2) IDS supplier log files. Multiple log files allow the team to run reliable post analytics and provide metrics on supplier performance. An additional user interface to the main DAS allows the test conductor to manage the Run ID, attack type, supplier, and access to start/ end data collection for an attack sequence. A secondary DAS logs data synchronously with the main DAS and is used when more bus channel inputs are required. DAS data files with preselected unique Run ID provides a distinct identifier for each attack test. Both the main and secondary DAS have very accurate internal clocks and an integrated 5 Hz GPS receiver to provide periodic sub-millisecond time pulses for synchronizing data collected between the two platforms. An additional application was run using Vector's CANoe with customized CAPL script to output a sync CAN message every 12 seconds (CAN ID: 0x7FA) on the main high-speed bus to represent a global CAN message timestamp for log synchronization.

As previously indicated, the project scope is limited to the use of direct wired attacks to vehicle CAN bus and assumes the attacker has already exploited an entry vector and gained access to vehicle CAN buses.

of IDS design bus monitoring, it was left to the discretion of the suppliers on which buses to monitor for anomalous behavior. The presumption is that anomalies are injected only on the main high-speed CAN bus, but may manifest themselves on other vehicle buses through a vehicle gateway (if implemented by an OEM).

5.1.1 Vehicle instrumentation

As indicated in section 5.1, the research team instrumented each test vehicle according to the proposed test-bed architecture. Figure 5 and Figure 6 show various instrumentation components used on one of the test vehicles. Vehicle CAN bus access was utilized with a “W” breakout harness at the OBD-II connector to allow multiple users simultaneous access to all available CAN buses. Figure 5 shows dual DAS monitors used by the rear-seated test conductor to manage the test protocol.



Figure 5: DAS Monitors for Test Identification and Monitoring

Typical dynamic road testing requires up to three test personnel: (1) scripted driver, (2) front passenger to log test details and initiate simulated attacks, and (3) rear passenger to run the data acquisition system as “test run coordinator” and monitor health of logging systems.

To achieve a flexible test environment, components were integrated on a modular platform in the rear of the test vehicle as shown in Figure 6. It includes two data acquisition systems (master/slave DAS), Silent-Cyber module (containing all scripted attacks for all three test vehicles), back-up battery for reserve capacity to support DAS loading (especially important with vehicle in the engine off/accessory on state), and associated wire harnesses to interface to vehicle power and communication buses. For versatility, all test equipment is securely attached to a mobile mounting platform for ease of transfer between the three test vehicles. Ratchet straps are used to secure test platform to vehicle for safety during dynamic and false positive testing.

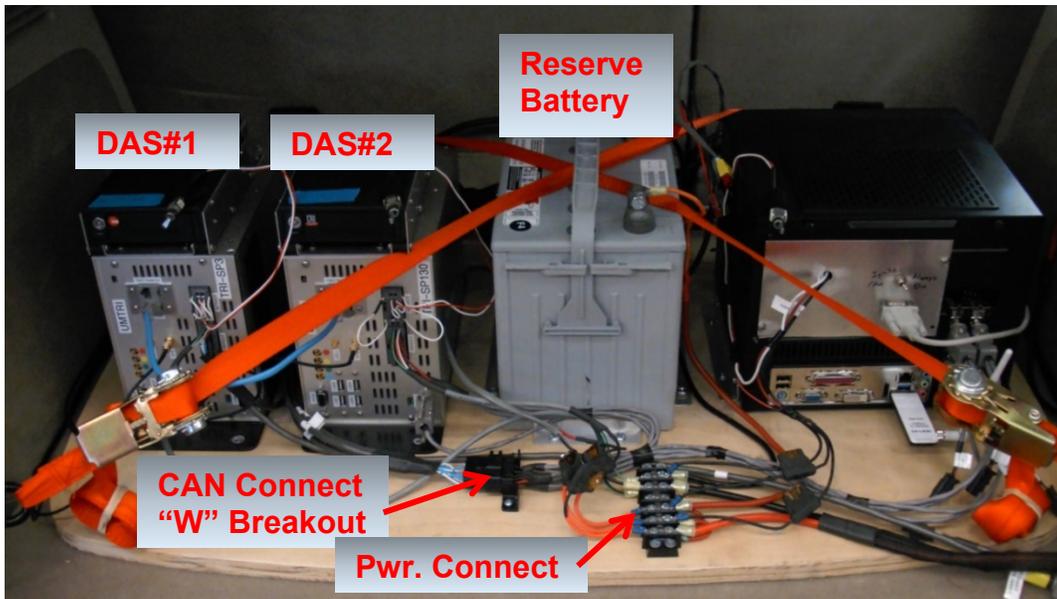


Figure 6: DAS Instrumentation

Additional test tools were utilized throughout the project to enable vehicle research and execute IDS performance assessments:

- One OEM provided the use of their custom diagnostic tool, interfaced through the OBD-II, permitting operation in two different modes: (1) to run various diagnostics “during” an IDS performance assessment session and (2) to clear fault codes when necessary (i.e., some simulated attacks would set vehicle fault codes).
- The team purchased a Vector Informatik “CANoe” tool utilizing Vector’s Communication Access Programming Language (CAPL) to clear codes in another OEM’s vehicle. Acquiring the OEM specific diagnostic tool was prohibitively expensive.

5.1.2 IDS integration

As indicated in Figure 4, the IDS solutions are integrated to the test vehicle CAN bus via the OBD-II port connector “W” cable interface. The IDS interface to OBD-II connector allowed for flexibility to switch between IDS solutions and/or test vehicles in an expedient manner when necessary. Figure 7 depicts a typical IDS integrated in a test vehicle. The IDS is physically located between front seats on the center console for ease of integration and the ability to monitor its functional status.

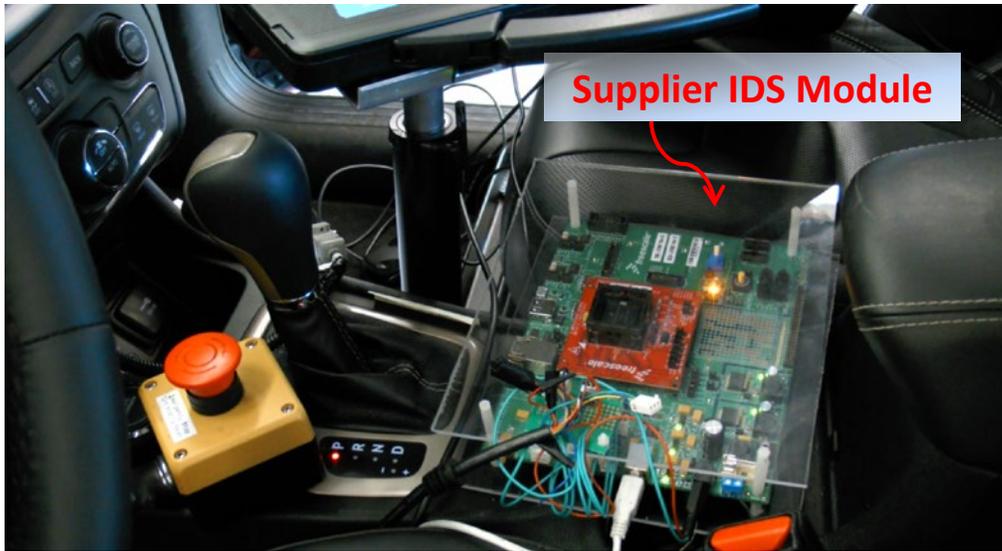


Figure 7: Example of a Prototype IDS Integrated in Vehicle Cabin

5.2 Supplier integration and calibration

To insure a successful and unbiased assessment landscape between the research team and the IDS suppliers, limited information was shared between the two project partners. General vehicle integration and operational conditions were established, however, to provide some level of design guidance to suppliers.

Information provided to suppliers:

- Vehicle make, model, feature content
- All vehicle CAN bus database files (.dbc files) provided by OEMs
- Simulated attack types (i.e., representing anomaly category types)
- Attacks would be injected onto main high-speed CAN bus only
- Performance assessment includes both static (engine on/parked) and dynamic vehicle operating conditions
- Naturalistic “long-drive” for eliciting false positive alerts (i.e., no simulated attacks)
- Diagnostic events would be exercised

Information not provided to suppliers:

- What attack message IDs would be sent
- When attack messages would be sent
- Details of specific attacks
- How many attacks would be used during assessments
- Performance assessment metrics to be used for performance (some IDS suppliers may infer metrics used based on previous experience with the research team on similar projects)
- Exact vehicle status/driving conditions during static and dynamic assessments
- Use of commercially available third-party dongle

As indicated in section 4.3 IDS suppliers followed a “training development protocol” agreed upon by both the research team and suppliers alike. This training occurred with a two-stage approach:

Stage 1: Off-Site Pre-Development:

- To allow algorithm development prior to visiting the team, suppliers were provided the appropriate vehicle CAN bus database files (.dbc file) by the OEMs. These databases describe all bus messages (message IDs, payload ranges, transmit rates, etc.) between transmitting and receiving ECUs. This is replicated for each CAN bus on each test vehicle. The team also shared its principal document “Supplier Version Test Methodology” (Test Plan) to suppliers. This document describes the project’s objectives, the test vehicles, test bed, and an overview of the anomaly categories (attack categories) and assessment metrics. The “supplier version” document is a subset of the overall project test methodology (less specific details about what would unfairly bias IDS designs for assessments). The test methodology document was a living document during the critical phase of the interaction with IDS suppliers such that updates were frequent to incorporate all IDS suppliers’ feedback. The document also defined qualifications to IDS suppliers such as a time stamping mechanism, alert detection acknowledgement message, and supplier log content.
- In addition, to help expedite IDS design work, suppliers would typically acquire a vehicle of very similar build content to help start in-vehicle algorithm development (supplier vehicles were not always exact replicas of actual project test vehicles). The team and suppliers also discussed new CAN bus messages (outside of OEM database files) required to supplement the data collection process for proper alert identification.

Stage 2: On-Site Development and Training:

- Although each supplier’s design approach is different, one commonality among suppliers is the condition to spend significant development time in the actual assessment test vehicle to adequately “train” and refine their algorithm. This is accomplished through extensive exposure to as many vehicle operating conditions as possible (both static and dynamic). At this stage of IDS product maturity, on-site algorithm training is very labor intensive in the sense that it requires the ability to exercise every conceivable vehicle operating condition. The on-site training process is iterative, and it is not uncommon to have multiple on-site training sessions for each supplier, continually striving to achieve an optimal level of performance.
- In addition, prior to actual product assessment, each supplier provided both a written user’s manual and an on-site demonstration of their respective IDS product. No IDS suppliers were on-site during assessments as every effort was made to eliminate any partisanship.

5.3 Attack scripts

A core element of this project is the development and use of simulated attacks to allow in-vehicle IDS investigation and assessment. CAN bus anomalies (simulated attack scripts) were designed utilizing prior knowledge of vehicle features to deliberately impact specific systems such as adaptive cruise control, forward collision warning, park assist, powertrain, cluster (IP) information, or HVAC. The intent is to create anomalies (attack scripts) that are subtle yet effective, stressing the IDS's ability to detect attacks while also allowing discrimination between IDS solutions. Execution of poorly scripted attacks would encompass designs detected by all IDS solutions and, therefore, would provide no useful information to delineate between competitive IDS implementations. Careful and iterative attack development was conducted on-site and validated in-vehicle to insure scripts utilized for this project were effective. Some attacks had the side benefit of providing vehicle visual/audible confirmation to the test assessor when issued.

As indicated in section 4.1, the previously indicated attacks were conducted in both stationary and in-motion vehicle scenarios. It is not uncommon to implement the same attack for both test environments. Simulated attack injection was managed by the test conductor via wireless laptop GUI interface to the simulated attack module.

5.3.1 Attack script development philosophy

Attack script development was managed by the research team and encompassed design guidance that fell under categories of anomalies as indicated in Section 3.4. The team made the recommendation to identify 8-10 attack scripts per anomaly type that would yield a total of approximately 35-45 attacks per vehicle (with some replication between static and dynamic vehicle states). The team estimated that this number of attacks would satisfy initial prerequisites of the project to test and discriminate between levels of IDS supplier performance (per vehicle). The attack developer, in cooperation with the research team, developed a library of potential attacks (per attack category per vehicle). The team only utilized a subset of the total attack scripts in actual IDS performance assessments based on their apparent impact to vehicle operation. There were no explicit specifications for total number of attacks to be injected per vehicle type. The team's first level approach to determine how many attacks to expose each IDS product was to be created from the total attack categories (true positive) described in section 3.4

For this project, the total number of simulated attacks injected per vehicle are as follows:

- Vehicle 1: Total simulated attacks = 44
- Vehicle 2: Total simulated attacks = 32
- Vehicle 3: Total simulated attacks = 32

The number of simulated attack scripts was determined based on the scope of project funding and the desire to use several different types of anomalies. This number may be adequate to reveal large differences in system performance but it is not expected to provide confident discrimination in the overall capability between, for instance, two systems that perform relatively well.

OEM stakeholders were not participants in the development of attack specifications, definition of attack philosophies, or part of the process to determine how metrics are weighted or classified.

5.3.2 Simulated attack examples

For informational purposes only, Table 3 highlights three examples of simulated attacks utilized on this project, one from each vehicle type.

Table 3: Simulated Attack Examples

DAS Attack I.D. (#)	“Attack Description”	Launch Type	NOTES	Attack Visual Effect	False Positive Case Avail?
83	RandomlySelectMsgFromBus	Script	This script will randomly select 20 arbitration ids and its data from the specified bus and replay them back at a random interval 10 times	None	None
12.31	Replay - Drive - 1st Gear	Script	When original message detected, sends transmission message with corrupt data= 1st gear	Doors Lock	Shift vehicle PRNDL in manual 1st gear
184	Passenger Seat Occupant Safety Info (5x faster)	Launch & Repeat	ID 256, message sent at abnormal rate	Pas airbag off illumination	None

5.4 Test Procedures

As previously indicated, in-vehicle IDS performance assessment consisted of three test sequences: stationary tests, in-motion tests, and an additional long-drive sequence (with purposely created unusual or fringe events to elicit potential false positive alerts). The general test cadence was to begin with the stationary test sequence followed by in-motion test sequences as described in the following sections.

5.4.1 Stationary test sequence

Stationary (static) test sequences took place in a garage area (engine running with exhaust vented) with the transmission in park. General vehicle features were enabled such as AC and audio that would be used in normal vehicle operation for testing comfort. No extraneous efforts were made to place vehicle in an unusual operating state. Many of the static simulated attacks are similar or identical to the “in motion” sequence of attacks. Typical test runs include the following steps.

- Test operator selects a specific test attack via attack module GUI (defined per test identification number)
- Test operator defines a “Run ID” to indicate a given descriptor for the DAS log
- Test operator starts and confirms IDS functional (i.e., logging)
- Test operator starts and confirms DAS log functional
- Test operator executes an attack via attack module GUI
- Test operator confirms attack sent on bus (via bus monitor or IDS output monitor, then stops - DAS log (Run ID))
- Test operator confirms if vehicle fault set (if so, clear associated DTCs)
- Repeat sequence for next attack type (leave IDS in run mode)

5.4.2 In motion (dynamic) test sequence

“In Motion” test sequences are simply that, injected attacks conducted while vehicle is in motion and, in some cases, specific to the test sequence (e.g., use of cruise control). A typical test run is very similar to the static case with the following steps:

- Test operator selects a specific test attack via attack module GUI (defined per test identification number)
- Test operator defines a “Run ID” to indicate a given descriptor for the DAS log
- Test operator starts and confirms IDS functional (i.e., logging)
- Test operator starts and confirms DAS log functional
- Test driver starts predefined drive sequence (settle vehicle speed to ~ 25-30mph)
- Test operator execute an attack during drive sequence via attack module GUI
- Test driver completes drive sequence
- Stop vehicle
- Test operator confirms attack sent on bus (via bus monitor or IDS output monitor, then stops DAS log (Run ID)
- Test driver confirms if vehicle fault set (if so, clear associated DTCs)
- Repeat sequence for next attack type (leave IDS in run mode)

Continual monitoring for vehicle faults is necessary and can be observed through instrument cluster warning indicators or with a diagnostic tool. If a fault is set because of an injected attack, it is noted and cleared before continued testing.

The in-motion test sequence was conducted on a 32-acre closed course. The research team determined it would best ensure safety by conducting dynamic testing within a controlled driving environment. Many of the injected attacks occurred with the vehicle moving on a simulated highway surface, typically at speeds between 25-30 mph and under nominal driving conditions. Figure 8 provides an aerial view of the test track used.



Figure 8: Test Track Used for Dynamic IDS Testing

5.4.3 False positive test sequences

The team conducted two independent assessment types that fall under the “false positive” test sequence:

1) False positive - Stationary/in-motion test events:

These tests consist of typical and fringe vehicle operations during both parked and driven conditions to elicit the IDS to identify “normal” CAN bus messages as “anomalous” (although no attacks are injected). Dynamic false positive tests can be executed on Mcity (closed test track) or public roads depending on test type.

2) False positive – Long-drive test sequence:

This test consists of a drive duration lasting approximately 3 to 4 hours. Depending on test vehicle type, it is assumed that some of the following sub-systems are not available on all vehicles and tests can be ignored accordingly. In addition, since no simulated attacks (anomalies) are used for the false positive test sequence, this test is conducted safely on public roads to expose the IDS to a variety of road types and naturalistic driving conditions.

Prior to the false positive long-drive sequence, the test driver verifies both the IDS and the DAS are functional and actively logging. The following long-drive scenario was conducted:

1. Pre-drive, with vehicle running, enable all enhanced driver features (if available).
 - 1) Lane keep assist
 - a. Active assist
 - b. Warning level high
 - 2) Forward/reverse sensing
 - a. Active
 - b. Warning level high
 - 3) Blind spot information system
 - a. Active
 - b. Warning level high
2. Begin vehicle assessment
 - 1) In parked condition, rapidly and sequentially exercise all PRNDL positions.
 - a. Exercise buttons in order (P-R-N-D-L).
 - b. Exercise buttons randomly.
3. Start drive from UMTRI to U.S. Route 23 to U.S. Route 12.
 - 1) On U.S. Route 23, exercise adaptive cruise control with steering wheel buttons.
 - 2) Exercise speed control (increment/decrement).
 - 3) Exercise gap control (increment/decrement).
 - 4) Exercise conflicting speed and gap inputs simultaneously.
 - a. Following a lead vehicle, increase speed while increasing gap.
 - b. Following a lead vehicle, decrease speed while decreasing gap.
4. Drive U.S.12 to Saline, then onto Clinton.
 - 1) Enable manual sport shifting
 - a. Select gears rationally (e.g., select gear appropriate to the speed and rate of acceleration).

- b. Select gears irrationally (e.g., attempt to enter high gear range while stopped or attempt to downshift while at high speed (only under safe conditions!)).
5. Drive Tecumseh-Clinton Highway, from Clinton to M50 west.
 - 1) Activate wipers in all modes (intermittent, low speed, high speed)
 - 2) Activate headlights, high beams, instrument cluster dimmer.
 - 3) On vehicles 1 and 2, attempt to open rear lift gate via instrument panel button (while vehicle in motion).
6. Drive M50 west to M52 south to Adrian.
 - 1) Exercise passenger climate/comfort/infotainment features
 - a. Climate control and vented/heated seats using traditional buttons
 - b. Climate control and vented/heated seats using touch screen interface
 - c. Audio controls using steering wheel and traditional buttons
 - d. Exercise various touch-screen interfaces
 - i. Climate controls
 - ii. Audio controls
 - iii. Navigation
 - iv. Vehicle settings
7. In Adrian, conduct a parallel park maneuver using the park assist feature (when applicable). Exit out using the park-out assist feature.
8. Enter Adrian Mall north vacant parking area.
 - 1) At a safe speed (<15 mph), release hood (bonnet) latch.
 - 2) While in motion (<15 mph), unlatch driver seat belt then open driver door (only under safe conditions).
 - 3) Stop vehicle. Stop IDS monitor and clear DTCs (if required). Turn vehicle off.
9. Restart vehicle. Resume IDS and DAS logging and return to UMTRI via reverse course. Drive vehicle as would be done under naturalistic conditions.

Exception: *The false positive long-drive test scenario as described in this section was not used with test Vehicle 3 due to OEM restrictions from use on public roads. To offset this limitation, a reduced duration false positive drive test sequence was implemented. The modified test sequence (approximate duration = 30 minutes) was conducted on MCity test track as an alternative solution.*

5.5 Summary of test data

All data collected by the DAS and supplier data logs were uploaded into an enterprise-level relational database for data processing and analysis. Over 50 hours of driving data was recorded and archived. For all tests, extensive notes captured details about each test, the success of the run, and any anomalous events. The notes then became part of the data archive to allow the analysis of only valid runs. Approximately 300 valid test runs were conducted to produce the results indicated in this report.

6. Data Analysis and Findings

6.1 Analysis description

Upon completion of all in-vehicle assessments, the researchers implemented custom Structured Query Language queries on all test vehicle DAS log files to generate summary performance metrics for each IDS solution (per vehicle). Query summaries essentially provide a pass/fail results for each test conducted. Performance metrics are compiled for each of the following test scenarios.

- 1) Vehicle stationary test with simulated attacks
- 2) Vehicle-in-motion test with simulated attacks
- 3) Vehicle false positive test scenarios including long-drive test (no simulated attacks)

Principal DAS data tables contain time-series recording of all CAN traffic with each message time-stamped. Along with the message ID, CAN bus identifier, length of the message payload, and the actual payload values were logged. For IDS that properly detected attacks, they produced “alert” messages (i.e., attack test script CAN bus anomalies) that were logged by both IDS as well as the DAS systems; this provided key indicators and measurements to verify that successful anomaly detection was achieved. In the case of “non-attack” test events, any alert messages logged as an attack by the IDS supplier provided the measure of false positive detection.

6.2 Tables of results

6.2.1 Data analysis - IDS performance breakdown per anomaly category

Table 4 through Table 7 represents IDS performance assessment results based on the anomaly categories identified in section 3.4. These tables offer insight into a supplier’s detection model highlighting strength and weaknesses, and more importantly give an indication of design philosophy in terms of how an algorithm is biased (i.e., a model emphasizing optimal TP or optimal FP). These design tradeoffs can be seen from the TPR (true positive rate) and FPR (false positive rate) (detection rates) summaries at the bottom of each table where an optimal TPR=100% and optimal FPR=0%.

Table 4: IDS Supplier Performance Breakdown (Vehicle 1-Phase 1)

Anomaly Category (Type)	Total Events	Supplier A		Supplier B		Supplier C	
		Ident.	Accy.	Ident.	Accy.	Ident.	Accy.
Cyclic (TP)	6	6	100%	3	50%	4	67%
Counters (TP)	4	4	100%	4	100%	4	100%
Status (TP)	34	32	94%	21	62%	25	74%
Bus Off (TP)	Not tested on this project per Section 3.4.4						
False positive “normal” (FP) - includes long-drive sequence	3	1	67%	0	100%	3	0%
False positive “non-normal” (FP)	4	0	100%	0	100%	2	50%
Total Detection Events	51						
TPR	44	42	95%	28	64%	33	75%
FPR	7	1	14%	0	0%	5	71%

Table 5: IDS Supplier Performance Breakdown (Vehicle 1-Phase 2)

Anomaly Category (Type)	Total Events	Supplier A*		Supplier B		Supplier C	
		Ident.	Accy.	Ident.	Accy.	Ident.	Accy.
Cyclic (TP)	6	6	100%	6	100%	5	83%
Counters (TP)	4	4	100%	3	75%	4	100%
Status (TP)	34	32	94%	29	85%	25	74%
Bus Off (TP)	Not tested on this project per Section 3.4.4						
False positive “normal” (FP) - includes long-drive sequence	3	1	67%	0	100%	1	67%
False positive “non-normal” (FP)	4	0	100%	0	100%	0	100%
Total Detection Events	51						
TPR	44	42	95%	38	86%	34	77%
FPR	7	1	14%	0	0%	1	14%

***NOTE:** For Vehicle 1 retest option, Supplier A decided not to participate in Phase 2 testing. Data shown is replicated from Phase 1 results.

Table 6: IDS Supplier Performance Breakdown (Vehicle 2-Phase 1)

Anomaly Category (Type)	Total Events	Supplier A		Supplier B		Supplier C	
		Ident.	Accy.	Ident.	Accy.	Ident.	Accy.
Cyclic (TP)	6	6	100%	6	100%	4	67%
Counters (TP)	4	4	100%	0	0%	3	75%
Status (TP)	20	17	85%	16	80%	17	85%
Bus Off (TP)	Not tested on this project per Section 3.4.4						
False positive “normal” (FP) - includes long-drive sequence	6	1	83%	0	100%	1	83%
False positive “non-normal” (FP)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Total Detection Events	36						
TPR	30	27	90%	22	73%	24	80%
FPR	6	1	17%	0	0%	1	17%

Table 7: IDS Supplier Performance Breakdown (Vehicle 3-Phase 1)

Anomaly Category (Type)	Total Events	Supplier A		Supplier B		Supplier C	
		Ident.	Accy.	Ident.	Accy.	Ident.	Accy.
Cyclic (TP)	12	11	92%	12	100%	9	75%
Counters (TP)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Status (TP)	20	20	100%	13	65%	14	70%
Bus Off (TP)	Not tested on this project per Section 3.4.4						
False positive “normal” (FP) - includes long-drive sequence	12	2	83%	0	100%	3	75%
False positive “non-normal” (FP)	5	0	100%	0	100%	0	100%
Total Detection Events	49						
TPR	32	31	97%	25	78%	23	72%
FPR	17	15	12%	17	0%	14	18%

6.2.1.1 IDS performance breakdown - discussion

As indicated by TPR and FPR results shown in Table 4 through Table 7, no IDS supplier was perfect in detecting all anomalies. Again, no attempt is made to rank entries in these tables. The performance quality of suppliers is determined by how well IDS products meet individual OEM specifications. The choice would be both objective (data driven) and subjective (based on corporate philosophy (design tradeoff between detection performance and risk of false detection)).

The IDS performance breakdown results offer another means to view performance data and are not entirely different from the metrics summary tables shown in section 6.2.3. However, it is another method of observing the data. Better resolution on how each IDS solution performed with respect to different types of simulated attack types can better define an implementation strategy by a supplier. For example, for true positive attacks, some designs may be more sensitive to cyclic versus counter-based anomalies. Whereas for false positive detection, some designs may be more sensitive to non-normal versus normal vehicle operator-induced operating conditions. The number of tests for each anomaly type was small, so caution is needed in interpreting results at the level of anomaly type.

Overall, TPR and FPR data appear to indicate a design tradeoff, thereby making the goal of an optimal detection/decision system an ongoing challenge. Many in the automotive industry would challenge what performance attributes of an IDS must be identified as an optimal binary classifier. One school of thought suggests a system that offers a TPR=100 percent detection is best (at the expense of FPR >0%). While for others, the idea of accepting “any” false positives (FPR >0%) far outweighs missed detection of an actual anomaly (TPR<100%). Again, this tradeoff is founded on OEM conditions originating from an organizational philosophy - what levels of detection are necessary or deemed acceptable for end-user consumption.

6.2.2 Data analysis - IDS detection rates (false positive)

The details of IDS performance results for all genuine “false positive/true negative events” (for benign events on both in motion and stationary sequences) are identified and categorized by each event and vehicle type and shown in Table 8 through Table 11. Ideal IDS performance is indicated with a false positive rate (FPR) = 0%.

Table 8: False Positive Discrete Events (Vehicle 1, Phase 1)

(‘1’=False Positive, ‘0’=True Negative)
(s = static test condition, d= dynamic test condition)

Benign Event	Supplier A	Supplier B	Supplier C
s-LeftTurnSigMsgOrig Stationary	0	0	1
s-AllSeatsUnbuck Stationary	0	0	1
s-ChgVehToPark Stationary	0	0	1
s-ChgVehToRev Stationary	0	0	1
d-AllSeatsUnbuck in Motion	0	0	0
d-ForwardCollWarnChime in Motion	0	0	0
d-False Positive Long-Drive Sequence	1	0	1
False Positives Identified	1	0	5
Total Events	7	7	7
FPR	14%	0%	71%

Table 9: False Positive Discrete Events (Vehicle 1, Phase 2)

(‘1’=False Positive, ‘0’=True Negative)
 (s = static test condition, d= dynamic test condition)

Benign Event	Supplier A	Supplier B	Supplier C
s-LeftTurnSigMsgOrig Stationary	0	0	1
s-AllSeatsUnbuck Stationary	0	0	0
s-ChgVehToPark Stationary	0	0	0
s-ChgVehToRev Stationary	0	0	0
d-AllSeatsUnbuck in Motion	0	0	0
d-ForwardCollWarnChime in Motion	0	0	0
d-False Positive Long-Drive Sequence	1	0	0
False Positives Identified	1	0	1
Total	7	7	7
FPR	14%	0%	14%

Table 10: False Positive -Discrete Events Results (Vehicle 2, Phase 1)

(‘1’=False Positive, ‘0’=True Negative)
 (s = static test condition, d= dynamic test condition)

Benign Event	Supplier A	Supplier B	Supplier C
s-Reverse Signal	0	0	0
s-Neutral Signal	0	0	0
d-Drive Signal 4th Gear	0	0	0
d-Cruise Control Accelerate	0	0	0
d-Cruise Control Decelerate	0	0	0
d-False Positive Long-Drive Sequence	1	0	1
False Positives Identified	1	0	1
Total	6	6	6
FPR	17%	0%	17%

Table 11: False Positive -Discrete Events Results (Vehicle 3, Phase 1)

(‘1’=False Positive, ‘0’=True Negative)

(s = static test condition, d= dynamic test condition)

Benign Event	Supplier A	Supplier B	Supplier C
s-Engage brake pedal	0	0	0
s-Engage brake pedal 50%	0	0	0
s-Turn on cruise via steering wheel	0	0	0
s-Put transmission in neutral (from park)	0	0	0
s-Manually shift to 2nd gear	0	0	0
s-Open all doors	0	0	0
s-Read/clear DTC's via diagnostic tool	0	0	0
s-Install automatic dongle	1	0	1
d-Turn steering wheel angle = 10°	0	0	0
d-Engage brake pedal = 50%	0	0	0
d-Engage parking brake pedal	0	0	0
d-Turn on cruise via steering wheel	0	0	0
d-Increase cruise control speed	0	0	1
d-Put transmission in neutral (from drive = 20 mph)	0	0	0
d-Put transmission in 1st gear from 3rd (manual shift)	0	0	0
d-Open all doors	0	0	0
d-False positive long-drive sequence	1	0	1
False Positives Identified	2	0	3
Total	17	17	17
FPR	12%	0%	18%

6.2.3 Data analysis - IDS metric summary tables

Utilizing all data gathered and identified in sections 6.2.1 and 6.2.2, and fulfilling the quantitative metric models defined in section 3.6, the following project IDS summary tables are constructed indicating suppliers' overall performance metrics (per vehicle type) as shown in Table 12 through Table 15.

Table 12: IDS Supplier Performance Metrics (Vehicle 1, Phase 1)

	TP	FN	FP	TN	Precision	Recall	F-Score Beta = 1.0	F-Score Beta = 0.5	Informed- ness	Marked-ness
Best→	Hi	Lo	Lo	Hi	1	1	1	1	1	1
Supplier A	42	2	1	6	0.98	0.95	0.97	0.97	0.81	0.73
Supplier B	28	16	0	7	1.00	0.64	0.78	0.90	0.64	0.30
Supplier C	33	11	5	2	0.87	0.75	0.80	0.84	0.04	0.02

Table 13: IDS Supplier Performance Metrics (Vehicle 1, Phase 2)

	TP	FN	FP	TN	Precision	Recall	F-Score Beta = 1.0	F-Score Beta = 0.5	Informed- ness	Marked-ness
Best→	Hi	Lo	Lo	Hi	1	1	1	1	1	1
Supplier A*	42	2	1	6	0.98	0.95	0.97	0.97	0.81	0.73
Supplier B	38	6	0	7	1.00	0.86	0.93	0.97	0.86	0.54
Supplier C	34	10	1	4	0.97	0.77	0.86	0.92	0.57	0.26

*NOTE: For Vehicle 1 retest option, Supplier A decided not to participate in Phase 2 testing. Data shown is replicated from Phase 1 results.

Table 14: IDS Supplier Performance Metrics (Vehicle 2, Phase 1)

	TP	FN	FP	TN	Precision	Recall	F-Score Beta = 1.0	F-Score Beta = 0.5	Informed- ness	Marked-ness
Best→	Hi	Lo	Lo	Hi	1	1	1	1	1	1
Supplier A	29	3	1	5	0.97	0.91	0.94	0.95	0.74	0.59
Supplier B	24	8	0	6	1.00	0.75	0.86	0.94	0.75	0.43
Supplier C	25	7	1	5	0.96	0.78	0.86	0.92	0.61	0.38

Table 15: IDS Supplier Performance Metrics (Vehicle 3, Phase 1)

	TP	FN	FP	TN	Precision	Recall	F-Score Beta = 1.0	F-Score Beta = 0.5	Informed- ness	Marked-ness
Best→	Hi	Lo	Lo	Hi	1	1	1	1	1	1
Supplier A	31	1	2	15	0.94	0.97	0.95	0.95	0.85	0.88
Supplier B	25	7	0	17	1.00	0.78	0.88	0.95	0.78	0.71
Supplier C	23	9	3	14	0.88	0.72	0.79	0.85	0.54	0.49

6.2.3.1 Metric Summary Tables - Data Observations

The following observations can be made from Table 12 through Table 15:

- 1) IDS supplier listings do not constitute a ranking order and are out of scope for this project. It is conceivable that interested OEMs would desire to acquire supplier rankings to determine which solutions are most effective. A ranking task is not part of this project and would be dependent on an IDS customer's conditions such as corporate philosophy, business model, safety considerations, and/or desired technical relevance.
- 2) The true negatives column requires further clarification. The TN numbers reflect properly classified (non-attacks) in the categories described in sections 3.4.5 and 3.4.6. Although these sections highlight false positive classifications to actual non-events, proper classification (no detection) of a negative event is classified as TN (i.e., messages invoked by normal vehicle behavior that are like actual attack messages or are "atypical" but not impossible events). Each long-drive contributes to at most one true negative.
- 3) The methodology used for observing false positives, as described previously in section 3.4, was not a rate-based approach; rather it was an approach to collecting false positives (number of false alerts per total message count). The research team intentionally and realistically attempted to elicit false positive "events." They chose not to count all normal CAN bus messages, as the number would be very large and time consuming for in-vehicle testing, as well as obscure the important differences that the tests reveal (i.e., that most false positives were attributable to tests designed to mimic drive events and conditions "similar" to attacks).
- 4) As previously indicated, the team anonymized IDS suppliers to remove any validity to ranking perceptions. However, as indicated earlier in this document, metric weights would be specified by the "customer" and will vary between customers. Overall ranking may also be result of a combination of quantitative and qualitative metrics and again reliant on IDS customer conditions. For example, perhaps an IDS solution successfully meets customer performance metrics; however, it only exists as a "beta" developmental-level product and not production-ready embedded design.
- 5) Although not exactly prominent in the results shown in Table 12 through Table 15, test metric summaries could help establish "tiers" of suppliers. Tiering may be more apparent if the number of IDS suppliers assessed was a larger sample size.
- 6) It was observed during this project that all IDS suppliers, in independent yet similar fashion, continually attempt to "balance their system" for optimal efficacy. This is done through iterative design tradeoffs striving to provide high accuracy at detecting true attacks (TP) and minimizing false detections (FP).

6.2.3.2 Metric summary tables - discussion

As indicated by the data in the metrics summary Table 12 through Table 15, no IDS performed perfectly, and under the test circumstances, none should perform flawlessly. The research team is confident that all suppliers' products would perform better given the following circumstances:

- 1) OEMs are more closely embedded with IDS suppliers providing more architecture information. Detailed design documents describing the control architecture and data flow between ECUs would provide more information to establish the boundaries on correct bus behavior and thus allow for easier/better detection of anomalies.
- 2) IDS suppliers co-developed their solution with OEMs during the entire vehicle development cycle. For this project, suppliers had only a limited number of weeks to integrate and train their solutions on production (test) vehicles before assessments were conducted (i.e., no OEM guidance was provided with respect to supplier algorithm development and integration).
- 3) Automotive OEMs had tighter CAN bus performance conditions. CAN is a very robust protocol for communications between ECUs; this robustness has been a great asset to the automotive industry but has also allowed for tolerance to system variability. Reducing the bus variability would allow easier detection of anomalies.

6.2.3.3 Metric summary tables - Phase 2 testing

As shown in Table 4 to Table 15, Vehicle 1 includes two distinct IDS performance assessments identified as "Phase 1" and "Phase 2," respectively. Due to Vehicle 3 logistics issues/timing constraints and with permission from NHTSA, the research team, in cooperation with participating IDS suppliers, elected to conduct an additional assessment of Vehicle 1 only. The intent for Vehicle 1 retest is to provide IDS suppliers with Phase 1 test results and allow them the opportunity to make design improvements for a second round of testing. The team did not provide feedback to IDS suppliers on exactly which attacks they failed, only overall ratings and guidance on categories of attack types.

IDS Supplier A opted out of Phase 2 testing since they felt the potential for improvement was limited without significantly more development time. However, their results from Phase 1 are replicated in Table 13 (Phase 2) for comparative purposes. It is important to recognize that IDS suppliers in general (except Supplier A) performed better in Phase 2 by improving true positive detections and reducing false positives.

6.3 Data analysis - IDS performance tradeoffs using receiver operating characteristic plots

Another method to illustrate the detection efficacy of an IDS-based binary classification system can be done using receiver operating characteristics (ROC) plots. A ROC plot shows the TPR versus FPR of a tested system. The ROC illustrates IDS design tradeoffs suppliers make when classifying events: one supplier's model may be developed (biased) with the goal of achieving a high probability of accurately detecting true attacks (at the expense of improperly detecting false attacks), while another supplier's model may be developed (biased) with the goal of achieving a high probability of accurately discriminating false attacks (at the expense of missing true attacks).

For this project, IDS performance data illustrated on ROC plots are shown only as discrete points where an ideal design yields results that are perfect and are depicted as a point located in upper left corner (also known as perfect classifier with coordinates (0,1)).⁷ This coordinate represents a perfect detector with a TPR=100% and FPR=0%. As depicted in Figure 9 to Figure 12, IDS performance (and design philosophies) is graphically observed as vector locations relative to the ideal classifier. By mapping supplier performance rates to an ROC plot, a visual summarization can be realized for the IDS tested on this project.

- IDS Supplier A design model emphasizes TPR relevance (max).
- IDS Supplier B design model emphasizes FPR relevance (min).
- IDS Supplier C design model emphasizes a balance between TPR and FPR.

Note that supplier design biases (model attributes/objectives) remain consistent between each vehicle type. Therefore, IDS model behavior appears to be relatively independent of test vehicle type. The diagonal reference line represents IDS detection/decision rates that are random in nature.

⁷ The ROC is a graphical method to illustrate the performance or diagnostic ability of a binary classifier system. These systems are typically displayed as a ROC "curves" instead of discrete points. Since the ROC curve is a graphical representation of a binary classifier system performance of "true positive rate" versus "false positive rate," the best IDS solution would demonstrate a curve that approaches the graphical location with a coordinate (FPR=0 and TPR=1; with Ideal coordinate x=0, y = 1,)

Figure 9: IDS Supplier ROC (Vehicle 1, Phase 1)

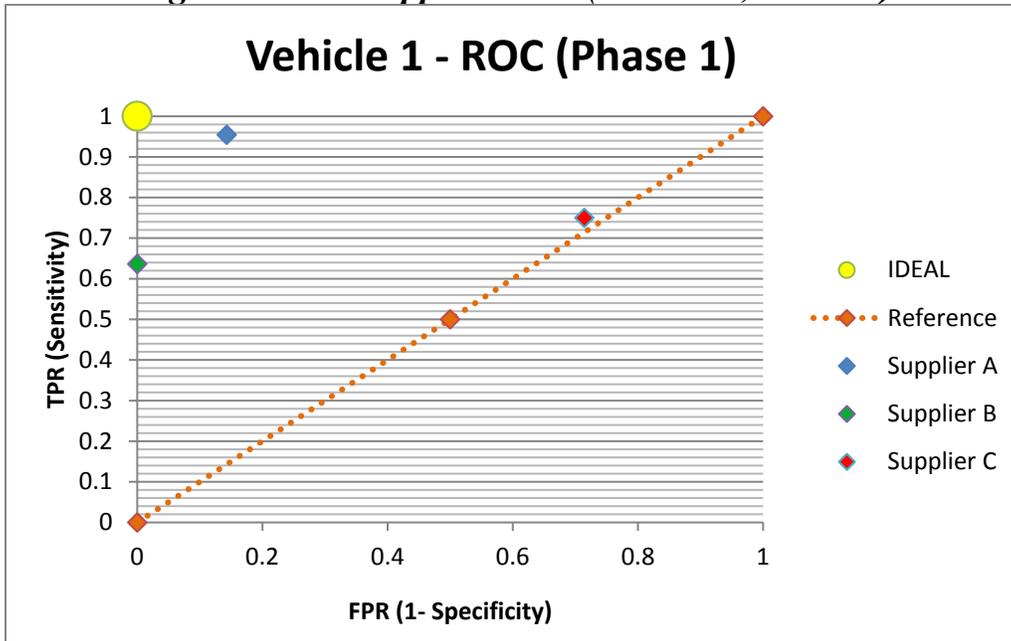
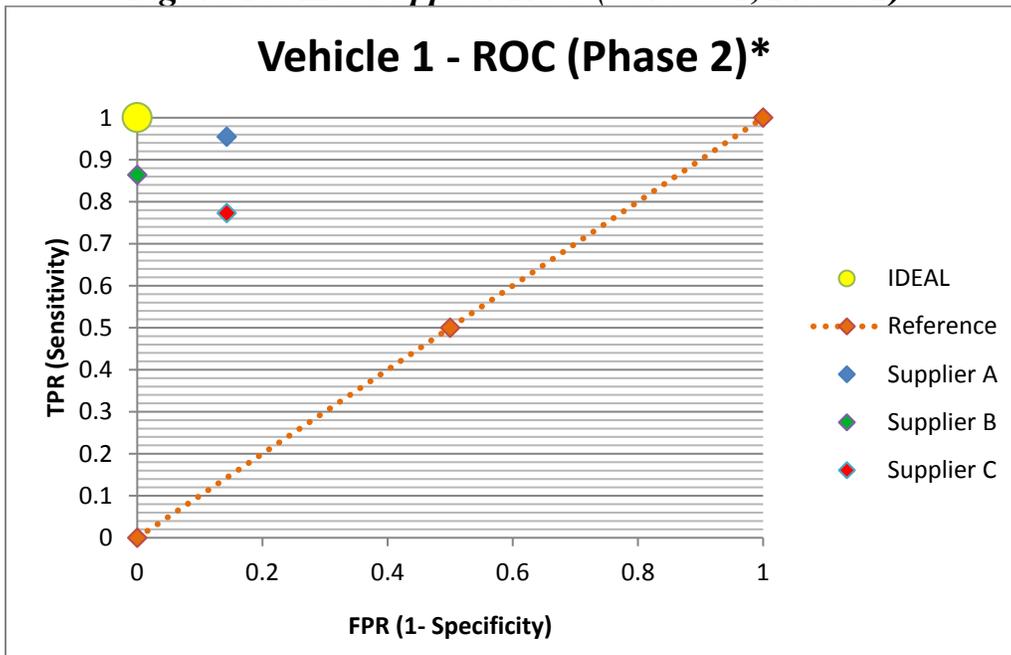


Figure 10: IDS Supplier ROC (Vehicle 1, Phase 2)



***NOTE:** As identified in section 6.2.3.3, IDS Supplier A opted out of Phase 2 testing since they felt the potential for improvement was limited without significantly more development time. However, their results from Phase 1 are included in the Phase 2 ROC as shown in Figure 10 for comparison purposes. Vehicle 1, Phase 2 plot does indicate IDS model improvement for Suppliers B and C (indicated by TP and FP rates “migrating” towards the ideal classifier).

Figure 11: IDS Supplier ROC (Vehicle 2, Phase 1)

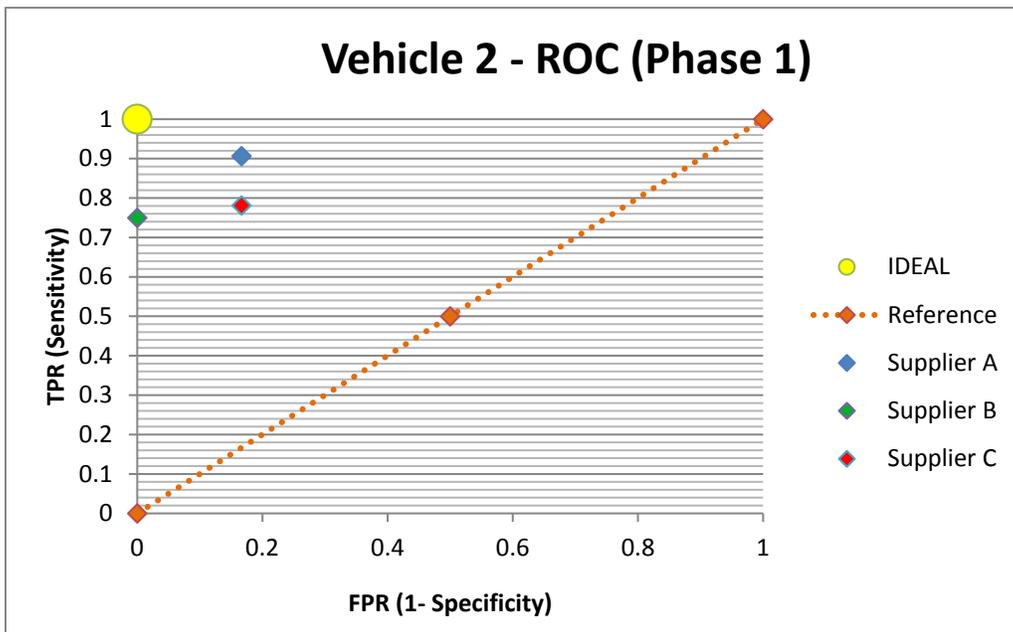
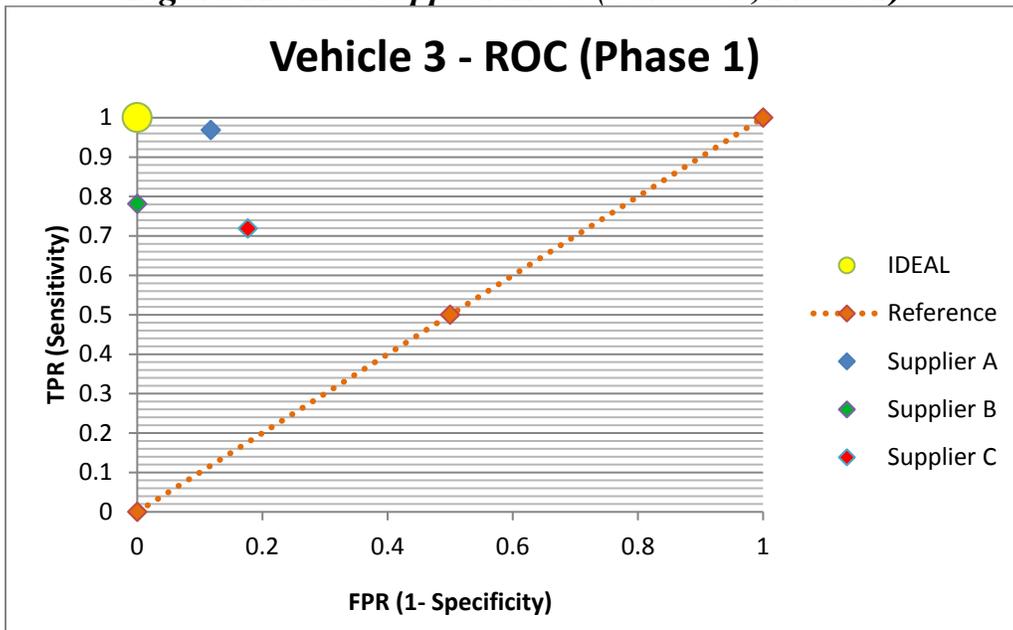


Figure 12: IDS Supplier ROC (Vehicle 3, Phase 1)



6.4 Design analysis discussion - project results

This project describes a methodology to test and assess IDS performance integrated on modern vehicles. Following the assessments, the logged data (logged IDS alerts) were postprocessed by the researchers via custom SQL queries for data mining/parsing to create an IDS performance mapping based on a standard binary classification system.

- True positive (accurate detection of an actual attack)
- False positive (detection of an attack when one is not present—false alert)
- True negative (accurate detection of a “non-attack”)
- False negative (detection of “non-attack when an actual attack occurs)

Utilizing the binary classification ratings previously described, each IDS performance can be rated based on accuracy to detect attacks (or non-attacks). Further numerical analysis is derived from the binary classified results to create additional weighted metrics such as:

- Precision and recall,
- F-score, and
- Informedness and markedness.

Utilizing all performance metrics indicated, metrics summary Table 12 through Table 15 were created to illustrate a scorecard for each supplier. The metric summary tables do not precisely rank competitive performance but do offer the potential for a “tiering” effect and are subjective to the reader based upon which metrics are weighted as critical. In general, True positive and false positive detection rates are always of interest, but remaining metrics do offer additional insight about which binary classifiers may be deemed more critical to a user of an IDS product.

Furthermore, another analysis tool that can be used to graphically guide an OEM to select a “preferred” IDS suppliers is use of ROC plots. ROC plots the TPR versus FPR and helps to identify comparative performances, but more importantly it helps to identify the supplier’s design and detection philosophy and its tradeoffs (i.e., a model that is more TPR- or FPR-centric). As indicated in the ROC plots shown in Figure 9 through Figure 12, Supplier A appears to be biased towards optimal TPR, Supplier B towards optimal FPR, and Supplier C appears to be a balance. The ideal design will identify TPR=100% and FPR=0%, an elusive goal.

7. Conclusions

7.1 Project overview

As electrification and developments toward full autonomy continue to evolve in the automotive industry, many OEMs have already launched or will be launching next generation vehicles that incorporate connectivity to other vehicles (V2V), to infrastructure (V2I), or to the Internet via cellular or consumer electronics (IoT). As a result, undesired side effects to this technology integration have caused concern and proven critically true with vehicle operation and, more importantly, safety as shown by security experts in recent years. In response to these new vehicle threat surfaces, existing well-established automotive suppliers as well as new start-up companies are responding with products offering intrusion detection, primarily for detection applications focused on CAN bus protocols.

NHTSA, the project sponsor, has undertaken this project to study and establish a methodology to assess intrusion detection systems integrated into modern vehicles.

Key objectives developed for this project:

1. Develop a methodology which illustrates an IDS performance assessment test process.
2. Develop in-vehicle test procedures applicable during static and dynamic IDS performance assessments.
3. Utilize interested OEM stakeholder vehicles as rolling test beds for IDS performance assessments.
4. Develop CAN bus simulated attacks (scripts that represent bus anomalies) to be injected directly onto vehicle CAN bus via the OBD-II data link connector (DLC).
5. Test the IDS on a variety of vehicle architectures and feature sets.
6. Develop a method to “tier” competing IDSs based on quantitative and qualitative metrics.
7. Develop a method to assess IDSs performances relative to an optimal model.
8. Develop recommendations for future IDSs assessment improvements/procedures.

An assessment methodology was created to establish a process for in-vehicle (rolling test bed) testing of anomaly-based intrusion detection systems. The project scope resulted in the assessment of three IDS suppliers (Suppliers A, B, C) on three unique vehicle platforms (Vehicles 1, 2, 3).

Vehicle OEM participants provided test vehicles and associated vehicle CAN bus network architectures including required proprietary CAN bus message databases (.dbc files). The research team established attack categories (types) to be implemented and developed a series of simulated attacks (CAN bus anomalies) for direct injection onto the test vehicle. Attack scripts were customized for each vehicle due to unique and proprietary message sets. The research team integrated each vehicle with data logging equipment to monitor all vehicle buses during IDS performance assessments. A suite of tests was conducted, including attack scripts and false-positive testing. Data logging included all bus data, capture of injected attacks, and IDS supplier alert messages. IDS vehicle application specifications included hardware integration via the OBD-II connector, with detection/alert notification to be done locally (i.e., no cloud-based analytics), and attack notification broadcast onto main high-speed CAN bus (HS-CAN) with special alert ID for logging purposes.

7.2 Technology observations

Based on the assessment of various IDS supplier products, the team offers the following technology insights:

- No IDS solution worked flawlessly. Even the best performing systems did not identify all simulated attacks (FN), or they incorrectly indicated attacks when none were occurring (FP).
- Investigative methods were established and exercised with “seasoned” cybersecurity suppliers on actual vehicles. It is a practical method to get a first-order estimate of the responsiveness of IDS.
- IDS implementation appears to be a positive tool to assist in vehicle cybersecurity. IDSs, as tested, are not a complete solution to automotive cyber threats, but they do offer a useful mechanism.
- IDS is a possible feature in next-generation vehicles. One advantage is that IDS can be quickly deployed while industry incorporates more security-by-design features into its products. Another benefit is to design and integrate the IDS in collaboration between the OEM and supplier during the design phase.
- The current state of IDS testing includes the ability to detect vehicle data bus anomalies and alert the user. Next generation products have or are being developed with product augmentations such as new detection/alert type strategies, prevention/mitigation capabilities, cloud based forensics, etc.
- IDSs, as tested, do not identify source of attacks.

General Observations:

- The test data is limited in this project, and actual testing in production would likely involve more tests with more anomaly varieties. However, this testing does achieve the goals of the project: to develop and illustrate a method to assess IDS.
- IDS product design types used on this project were demonstrated as an “add-on” CAN bus node (via the OBD-II diagnostic connector).
- IDS product designs used on this project were developed completely independent of any OEM support or guidance. Co-development would certainly lead to improved performance.
- Simulated attacks (anomalies) were injected directly onto CAN bus via the OBD-II connector (i.e., the project proposal explicitly defines and assumes that the CAN bus and/or its associated components were already compromised, allowing direct access to vehicle networks).

7.3 Technology improvements

Based on the assessments of various IDS supplier products in this project, the following list of potential technology improvements are suggested:

- More training time for the IDS on the vehicle: It is generally recognized among the IDS community that the more time an IDS solution (and its design team) is exposed to in-vehicle training, the greater the probability and confidence for improved performance. Atypical or unusual events are difficult to predict or elicit. Additional IDS training time in-vehicle will increase this probability and accuracy of capturing unique events.

- Cloud assistance: Industry wide, long-range goals for IDS will likely include continued real-time onboard detection and some form of real-time mitigation strategies. Industry indications highlight the potential of cloud based fleet-wide data analytics/forensics, post processing of IDS efficacy, and fleet-wide management of firmware upgrades with cloud-computed parameters for the onboard IDS.
- Fingerprinting: Future in-vehicle IDS threat detection enhancements may include new features to detect an attack source via means of “fingerprinting” system-wide physical properties of all CAN bus nodes. This will assist the quality and speed of anomaly detection.

8. Appendix A: Support Material for IDS Testing

To support a false positive dynamic vehicle test and attempt to illicit a forward collision warning (with or without brake mitigation), the team used an existing institute surrogate vehicle target that accurately simulates radar reflective properties exhibited by modern vehicles. The target is capable of withstanding vehicle strikes (rear-end collisions) with no damage to the test vehicle. Test conditions included a stationary surrogate target and approaching test vehicle with a constant speed $\cong 15$ mph. This target used for this test is shown in Figure 13.

NOTE: Several metallic radar reflective vehicle elements are embedded within the target structure and are not explicitly visible for durability and safety considerations (e.g., rear brake reflectors, rear axle components, exhaust, rear window roof line, etc.).

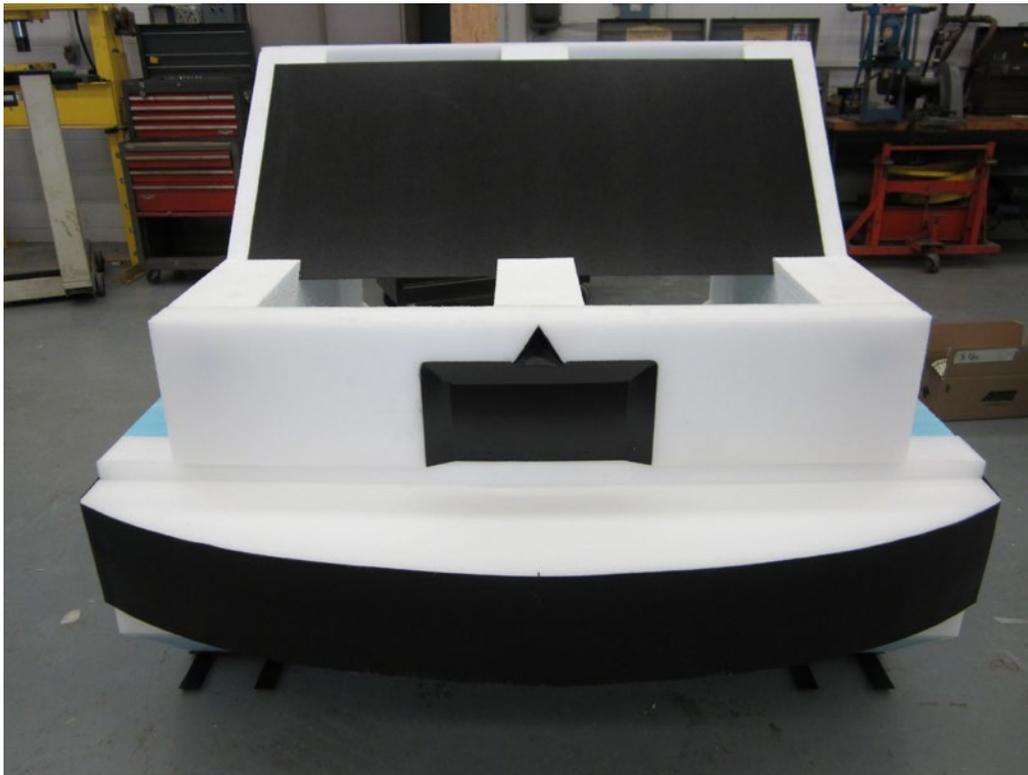


Figure 13: Surrogate Vehicle Target Used for FCW Assessments

9. References

1. University of Michigan Transportation Research Institute. (2015). *IDS vendor questionnaire*. Ann Arbor, MI: Author.
2. Valasek, C., & Miller, C. (2014). *Adventures in automotive networks and control units*. Seattle: IOActive, Inc.
3. Society of Automotive Engineers. (2001 et seq.) *SAE J1962, Diagnostic Connector*. (Revised nine times since introduced in 2001). Warrendale, PA: Author. [Editor's Note: In 2006, the Society of Automotive Engineers changed its formal name to SAE International.]
4. Koscher, K., Czeskis, A., Roesner, F., Patel, S., Kohno, T., Checkoway, S., ... Savage, S. (2010). *Experimental security analysis of a modern automobile*. Paper delivered at IEEE Symposium on Security and Privacy, Oakland, CA, May 16–19, 2010.
5. Checkoway, S., McCoy, D., Kantor, B., Anderson, D., Shacham, H., Savage, S., ... Kohno, T. (2011). Paper delivered at *Comprehensive Experimental Analyses of Automotive Attack Surfaces*, USENIX Security, August 10–12, 2011.
6. Miller, C., & Valasek, C. (Date unknown). *Adventures in automotive networks and control units*. Self-published as illmatics.com. Retrieved from http://illmatics.com/car_hacking.pdf
7. Miller, C. & Valasek, C. (2013) *Adventures in Automotive Networks and Control Units* (Video presentation). DefCon 21 Hacking Conference, August 1-4, 2013. Video available at <https://media.defcon.org/DEF%20CON%2021/DEF%20CON%2021%20slides/DEF%20CON%2021%20Hacking%20Conference%20Presentation%20By%20Charlie%20Miller%20and%20Chris%20Valasek%20-%20Adventures%20in%20Automotive%20Networks%20and%20Control%20Units%20-%20Slides.m4v>
8. Miller, C., & Valasek, C. (2015, August 10). *Remote Exploitation of an Unaltered Passenger Vehicle*. Self-published as illmatics.com. Retrieved from <http://illmatics.com/Remote%20Car%20Hacking.pdf>
9. Spaar, D. (2015, February 5). *Beemer, Open Thyself! – Security vulnerabilities in BMW's ConnectedDrive*. (Web page in online “C'T magazine für computer technik”). Hanover, Germany: Heinz Heise Media Company. Available at www.heise.de/ct/artikel/Beemer-Open-Thyself-Security-vulnerabilities-in-BMW-s-ConnectedDrive-2540957.html
10. Maradana, S. (2012, June 1). *CAN Basics* (Web page). Self-published. Retrieved from <https://automotivetechnis.wordpress.com/2012/06/01/can-basics-faq/>
11. International Organization for Standardization. (2015). *ISO 11898-1, Road vehicles – Controller area network (CAN) -- Part 1: Data link layer and physical signaling*. Geneva: Author.

DOT HS 812 708
April 2019



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