Analysis of the DoIP Protocol for Security Vulnerabilities

Patrick Wachter  
patrick.wachter@mercedes-benz.com  
Mercedes-Benz Tech Innovation GmbH  
Ulm, Germany

Stephan Kleber  
stephan.kleber@mercedes-benz.com  
Mercedes-Benz Tech Innovation GmbH  
Ulm, Germany

ABSTRACT

DoIP, which is defined in ISO 13400, is a transport protocol stack for diagnostic data. Diagnostic data is a potential attack vector at vehicles, so secure transmission must be guaranteed to protect sensitive data and the vehicle. Previous work analyzed a draft version and earlier versions of the DoIP protocol without Transport Layer Security (TLS). No formal analysis exists for the DoIP protocol.

The goal of this work is to investigate the DoIP protocol for design flaws that may lead to security vulnerabilities and possible attacks to exploit them. For this purpose, we deductively analyze the DoIP protocol in a first step and subsequently confirm our conclusions formally. For the formal analysis, we use the prover Tamarin. Based on the results, we propose countermeasures to improve the DoIP’s security. We show that the DoIP protocol cannot be considered secure mainly because the security mechanisms TLS and client authentication in the DoIP protocol are not mandatory. We propose measures to mitigate the vulnerabilities that we confirm to remain after activating TLS. These require only a minor redesign of the protocol.

CCS CONCEPTS

• Security and privacy → Formal security models; Security requirements; Network security; Embedded systems security; • Networks → Protocol testing and verification.

KEYWORDS

DoIP, security assessment, formal analysis, network protocol

1 INTRODUCTION

Modern cars use more than 70 electronic control units (ECUs) and this number will continue to rise [18]. When the number of ECUs in cars was lower, it was relatively easy to maintain and update them. In the workshop, with a tester directly connected to the car via dedicated wiring, the diagnostic data was read and minor updates were installed. However, the requirements for modern cars changed and nowadays it is desired to read out diagnostic data from anywhere via remote diagnostics. Over-the-air updates must also be possible [1]. Due to the ever-increasing number of ECUs and their increasing complexity, such updates are becoming larger, in some cases several gigabytes. This is no longer feasible with conventional bus systems such as Controller Area Network (CAN). This is why Ethernet and the Internet Protocol (IP) were adopted in the car. As a transport protocol the “Diagnostic communication over Internet Protocol (DoIP)” is used in this context. Unified Diagnostic Services (UDS), which is traditionally used over CAN, is the application protocol also used with DoIP [7, 8, 12]. The diagnostic interface allows access to information of the ECUs. It can be used to retrieve emission-related diagnostic data or to perform manufacturer-specific functions, such as calibrating technical components and software updates [7]. However, the diagnostic interface of cars can also be used by attackers to gain access to the vehicle’s electronic system.

In this paper, we examine the security of DoIP and perform a formal analysis of individual protocol phases. We thus provide a thorough assessment of the design’s robustness against malicious action that could undermine a vehicle’s functionality and safety.

2 BACKGROUND AND RELATED WORK

DoIP is defined in ISO 13400 [7, 9–11] for the usage with the User Datagram Protocol (UDP) for broadcasting initial messages and with the Transmission Control Protocol (TCP) after a session is established. DoIP covers aspects of the layers one to four of the Open Systems Interconnection (OSI) basic reference model [6] as illustrated in Figure 1. Also, the usage of Ethernet, IP and some auxiliary protocols is defined in the specification [7]. In the latest version of the standard, the use of TLS has also been added [11].

In 2011, Lindberg was the first to examine a late draft version of the DoIP protocol [15] for its security properties. When he authored his thesis in 2011, DoIP had not yet officially been released, so there is an urgent need to revisit and investigate the protocol again. Lindberg concluded that DoIP as of 2011 is not a secure protocol...
without additional measures. His findings reveal that one of the biggest vulnerabilities is the lack of authentication and of ensuring data integrity. He also notices ambiguities in the specification and a missing plausibility check for the validation of data in received messages [15].

Published in 2016, Ajin et al. compared different technologies in vehicle networks and gave a security analysis of DoIP [1]. Ajin et al. came to the same conclusion as Lindberg: Various security vulnerabilities exist in DoIP. In 2016, TLS was not yet present in the DoIP protocol specification.

Matsubayashi et al. evaluated attacks against UDS on DoIP [16]. They used a previous version of the DoIP protocol in which TLS was not yet present and found three attacks through the analysis: The first one is authentication avoidance in UDS. The other two attacks are man-in-the-middle (MITM) attacks by session hijacking through vehicle announcement messages and vehicle identification responses. They have demonstrated these attacks in an experimental environment and presented countermeasures for them [16].

Kleberger and Olofsson addressed the issue of how diagnostic data can be transferred securely, and how the diagnostic infrastructure in workshops can be secured [13]. To accomplish this, they compared four different options and concluded that Internet Protocol Security (IPsec) is the approach to take. It is easy to deploy and to maintain, although tools would have to be developed to help manage the peer authentication database (PAD). IPsec would also secure remote vehicle diagnostics over the internet. The key agreement protocol IKE can be replaced by a protocol specially designed for the use case, which distributes session keys and security policies only to authorized equipment [13]. The paper was written before TLS was part of DoIP.

Most related work on DoIP security discusses the versions without TLS. Its addition requires revisiting their findings and may render solutions like IPsec obsolete. Our paper analyzes the current protocol version and addresses the need for an updated security assessment.

Lauser et al. examined the status of the analysis of automotive vehicle protocols. Therefore, they give an overview of tools for formal analysis and, as an example, analyze AUTOSAR’s Secure Onboard Communication (SecOC) with Tamarin [14]. As future work, they propose a formal analysis of the DoIP protocol and, especially, DoIP with TLS. They conclude that formal analysis with a symbolic model is well suited for automotive protocols: Suitable tools exist that provide a quick and easy way to analyze automotive protocols [14].

### 2.1 Unified Diagnostic Services and Use Cases

The UDS protocol is defined in ISO standard 14229 and is used for diagnostic services requests and replies. A tester connected to the vehicle uses UDS in a client-server relationship with the tester being the client and the vehicle being the server [12].

Connecting a tester allows different use cases. During the production of the vehicle, DoIP is used to activate the software of the vehicle, to correct errors via software, or to detect hardware failures like broken sensors. During the vehicle lifetime, it is possible to read Diagnostic Trouble Codes (DTC) to find errors and clear them. It is also possible to read various parameters of the car, including the temperature, the state of charge, or the Vehicle Identification Number (VIN). In addition, diagnostic sessions can be initiated: Among other things, this allows the testing of safety-relevant features. The last use case is the modification of the ECU behavior: This is possible through resets, firmware flashing, or changes of settings [12]. Since UDS per se has no security protection for payload data and its usage may have impact on a vehicle’s safety, DoIP that is used as transport protocol needs to ensure the diagnostics security.

### 2.2 Diagnostic Communication over Internet Protocol (DoIP)

The ISO document 13400 [7, 9–11] defines the DoIP protocol as a communication protocol for automotive electronics to transport UDS messages. DoIP was developed while emissions-related diagnostic data first became mandatory [7]. The goal of ISO 13400 is to provide a standardized in-vehicle interface that separates the vehicle network from external test equipment and provides a long-term stable communication interface with the vehicle [7]. To discuss the security of the protocol’s design, we establish the basic principles of DoIP.

A DoIP server typically is a part of an ECU and it responds to requests by a client entity. The client typically is an off-board tester but can also be an on-board test device [7]. A vehicle can have multiple DoIP entities and there are several possible network configurations that DoIP can work in. The options are (1) to directly connect external test equipment to a vehicle via dedicated physically separate wiring, (2) a network connection between one vehicle and one test device, (3) the connection of multiple vehicles and one tester, or (4) one vehicle connected to more than one tester [11].

The communication between a client and a server entity using DoIP can be divided into three phases according to the message payload types:

- Vehicle announcement and vehicle identification phase
- Routing activation phase
- Diagnostic communication

**Vehicle announcement and identification phase.** Initially, the test device needs to identify each vehicle and its DoIP entities during the vehicle announcement and identification phase. This phase is performed via UDP and can be done in one of two alternative ways regardless of the network configuration [11, Figure 11]: Either, the DoIP-server entity, typically a gateway or entity of the vehicle, sends the vehicle announcement message three times as soon as it is connected to the network, or the test device can request a vehicle identification. The tester sends a vehicle identification request message to the vehicle, which responds with the vehicle identification response [11]. The vehicle announcement message and the vehicle identification response contain the same information. One part of the vehicle announcement or identification process is the synchronization feature. It is intended to synchronize the decentralized DoIP entities’ identification throughout the vehicle. The exact synchronization method is left to the vehicle manufacturer [11].

**Routing activation phase.** After the announcement phase, the tester must establish a TCP connection to the vehicle and then
activate the routing. If a secure connection is requested and supported by the implementation, a TLS connection is established. The DoIP gateway forwards received data from the diagnostic messages to the DoIP entities in the vehicle according to the address information [11]. This is called routing, is done on the vehicle-specific network transport protocol [11], and is unrelated to IP routing that takes place on the OSI network layer.

Diagnostic communication. If the routing activation was successful, diagnostic messages can now be exchanged via the TCP connection. When a DoIP-server entity receives a message, first, the DoIP header handler is called. If it is a diagnostic message, it is processed by the diagnostic message handler. The connection termination happens through the TCP teardown mechanism, after which all resources are cleaned up. If it is not closed regularly after usage, a general inactivity timer or an alive check message can close the connection. If a secure connection was used through TLS, the socket is closed through the TLS mechanisms [11].

With the power mode information request, a client can retrieve if the vehicle is in diagnostic power mode. This mode affects functions of the DoIP servers in the vehicle and its status is reported as either: not ready, ready, or not supported. Not ready means that not all servers that can be reached via DoIP can communicate. When the vehicle is in diagnostic power mode, it responds with ready and all servers can communicate. If the power mode information request message is unsupported, it returns not supported. The client can use the power mode request message to check if the vehicle is in the correct power mode to perform reliable diagnostics [11].

Structure of the DoIP messages. The header of a DoIP message is located at the beginning of each message and has a total length of 8 bytes. Figure 2 shows the structure of a DoIP header. The used protocol version is at the first position and has a length of 1 byte. At the time of this writing, there are three versions:

- 01₁₆: ISO/DIS 13400–2:2010
- 02₁₆: ISO 13400–2:2012
- 03₁₆: ISO 13400–2:2019 [11].

Position two contains the inverse protocol number to ensure that a correctly formatted DoIP message was received. The next position is the payload type, with a length of 2 bytes, followed by the payload length. The payload length field is limited to 4 bytes, which limits the payload size to 4 GB. The maximum allowed payload length is additionally dependent on the transport layer used [11].

Security Requirements. DoIP is used for the transmission of diagnostic data in UDS messages and, thus, the security of the diagnostic communication is inherently dependent on DoIP’s security. The security properties that are necessary to ensure secure diagnostics are confidentiality, integrity, availability, access control, freshness, and data origin authenticity. Confidentiality is essential since an attacker who obtains information and commands by eavesdropping during a diagnostic data transmission can use these to find vulnerabilities and critical information to use in subsequent attacks. It is important to ensure integrity so that unauthorized persons cannot manipulate data in the messages and cause unintended behavior that may be harmful. Interruptions of the availability when the receiver processes and answers DoIP messages must not endanger any human. Only legitimate tester devices should be able to read out sensitive diagnostic data to prevent information leakage. The freshness of the messages must be ensured so that no copy of a message can be replayed later in an inappropriate situation. For example, the same message that is innocuous at the workshop may become dangerous on the road if it is delayed or replayed. For data origin authenticity it should be ensured that only verified sources send messages and can also prove that they are verified. Otherwise, an attacker could pretend to be an authorized user and send messages that manipulate ECU behavior in a harmful way.

2.3 Tamarin

Formal analysis uses software tools to prove the secure design of cryptographic protocols. This is done by writing a model of a protocol and its usage. Security queries can then be used to check the security properties of the protocol. Various proof tools exist for this purpose, such as Tamarin [2] or ProVerif [3]. As input, they require a model of a security protocol, the properties of the adversary, and lemmas for the required security properties of the protocol [2]. With this information, the prover constructs a proof which includes verification and falsification whether the protocol fulfills the security properties in question. Tamarin has an interactive mode for evidence and attack graphs, where manual and automatic proofs can be started.

We use Tamarin [2] to investigate DoIP, since it is a powerful tool for symbolic modeling and security protocol analysis. It has been used to formally analyze many protocols, including TLS 1.3 [4]. In their paper on formal analysis of automotive protocols [14], Lauser et al. analyzed SecOC with Tamarin. They recommend Tamarin for the analysis of further automotive protocols [14].

For DoIP, TLS 1.2 and TLS 1.3 can be used to provide an encrypted and signed channel, which provides a confidential and authentic data transmission. Cremers et al. analyzed TLS 1.3 [4] with Tamarin and Houmani and Debbabi formally analyzed TLS 1.2 [5]. According to their results, TLS provides a secure communication channel, ensuring encrypted, authentic, integrity-protected, and freshness-preserving data transmission. The TLS-specific key exchange can be considered secure [4].

2.4 Attacker Model

The diagnostic interface via UDS is necessary to enable repairs with the large number of ECUs in modern vehicles. This is why profound changes to the vehicle can also be carried out via the diagnostic interface. Attacks through the diagnostics interface include to read and delete DTCs, which could lead to greater subsequent damage and thus higher costs for the owner of the car due to the non-detection of a fault. It would also be possible to read out sensitive data about the car or even personal data about the owner. The deactivation of security-relevant functions is also conceivable.
For special repairs it is necessary to temporarily switch off safety-
relevant functions, such as brakes. This is achieved via the car’s
diagnostic interface in a workshop. If an attacker exploits this by
preventing the function from being activated after the repair, the
vehicle is a danger to drivers and other road users. One of the most
critical attack vectors is the flashing of unapproved software to the
ECUs, which may have different intentions. One can attempt to
tune the car to get more performance out of it via manipulated soft-
ware. This may result in broken safety measures that will result in
dangers for the road user. Thieves could disable important systems
like the immobilizer by flashing new software. Attackers could also
deactivate other functions that are necessary for driving. All of
these diagnostic functions are typically conducted using UDS.

For such attacks, the adversary requires to modify or in some
cases only read from the network communication. Such an attacker
may be eavesdropping or performing session hijacking during a
running diagnostic session in vehicle production or in a workshop,
which may violate confidentiality and integrity. During normal
operations, i.e., the regular car usage when driving on the road,
attacks may include replay or spoofing of valid messages using
the attackers capability to inject messages into the network, which
primarily violates the integrity with potential safety impact. This
adversary is approximated by the Dolev-Yao attacker. They can
read, modify, intercept, and inject new messages on the network.
The standard attacker in Tamarin models is a Dolev-Yao adversary,
which we use in our models in Section 4.

3 SECURITY ANALYSIS

We organize the deductive security analysis in this section and
the formal analysis using Tamarin in the subsequent section into
subsections that resemble the DoIP protocol phases: the vehicle
announcement and identification phase, the routing activation, and
the diagnostic communication. We preprend a generic consideration
of the security of the DoIP header to the discussion of the phases.

We analyze the specification of ISO 13400–2 (2019) [11] and compare
it to the results of the analysis [15] of the draft version from 2011.
Our analysis is the first to consider the addition of TLS to the
standard, which is the major change between the standard versions.
All references to the standard are based on the latest version from
2019. In this section, we refer to tables, state machines, as well as
requirements in the standard using the naming scheme DoIP-xxx
that is used in the ISO 13400–2 document.

3.1 DoIP Header

3.1.1 Existing Measures. When a DoIP entity receives a message,
it first calls the DoIP header handler [11, Figure 16]. Some mecha-
nisms are built into the DoIP header handler to protect the DoIP
entities. According to requirement DoIP-031 [11], each DoIP entity
shall ignore packets that have a multi- or broadcast address as the
source IP address. This helps to prevent an amplification attack:
One malicious broadcast packet would trigger one reply packet
from each node in the network.

The requirements DoIP-039 [11] and DoIP-040 [11] are intended
to prevent NACK storms: DoIP-client entities shall not respond
to an invalid DoIP message from a DoIP entity with a NACK in
the header. Sending NACK messages is only allowed for the DoIP-
server entities, but not for the clients. Servers ignore incoming
negative acknowledged messages. The standard specifies exactly
when a message should be discarded, for example when a message
is too large and a buffer overflow would be possible. This measure
prevents overloading the network and server capacities.

3.1.2 Vulnerabilities. The header contains the protocol number
and its inverse, to ensure that correctly formatted messages are
received. However, the two protocol numbers are only 2 of the
8 bytes of the header. Therefore, it is a poor integrity check, not
only from a security perspective. According to Lindberg, this was
already the case in the draft version and has not changed with the
current version [15].

3.2 Vehicle Announcement and
Vehicle Identification

3.2.1 Existing Measures. The specification limits the number of
vehicle announcement messages sent into the network to three. By
limiting the number of repeated transmissions, a denial of service
vulnerability by toggling the connections of DoIp entities on and off
is mitigated if an attacker has not enough control over the entities
to unrestrictedly send messages into the network themselves. This
is a weak mitigation for a weak kind of attacker that has severely
limited control over the network and any of its entities.

As specified in DoIP-051 [11], the DoIP entities send the vehicle
identification responses after a random waiting time. Otherwise, it
would be possible to overload the network, since all DoIP entities
would respond to a vehicle identification request at the same time.
This is an effective functional network protection mechanism rather
than a security measure.

3.2.2 Vulnerabilities. In the vehicle identification phase, no au-
thentication is provided, which is why it is possible for attackers to
send false information as a response. The adversary does not even
have to establish a TCP connection for this, since this phase runs
via UDP. They can respond to requests with their own IP address
and pretend to be a vehicle. Also lacking any integrity protection,
all fields in the response can be changed by an adversary. This
vulnerability was already present in the draft version [15].

Figure 10 and Section 6.3.2 in the DoIP standard [11] differ in
the description of the procedure when a DoIP entity has the
sync status incomplete. According to the standard’s Figure 10 [11],
vehicle identification request messages are sent again after the
vehicle_discovery_timer has expired. In the textual description,
a request should only be sent to the entity that has set the sync
status to incomplete. Such an inconsistency in the definition may
allow adversaries to fingerprint which implementation is running on
a system. If an implementation has a particular vulnerability,
this can targetedly be exploited [11, 15]. Besides this still-present in-
consistency, further inconsistencies between individual definitions
existed in the draft version [15], but these are no longer contained
in the current version.

Another vulnerability is associated with the sync status: it can be
exploited for a denial-of-service attack. The attacker is an additional
node in the network and sends spoofed vehicle identification re-
sponses with sync status set to incomplete. Because of this message,
the client needs to wait for the server to be synced and then start again with a vehicle identification request. As client and servers are affected by this attack, the vehicle identification fails and the tester cannot connect to the vehicle. This attack [15] was already possible in the draft version.

### 3.3 Routing Activation

#### 3.3.1 Existing Measures

After the vehicle identification phase and the establishment of a TCP connection, the client must activate routing. At this point, TLS and thus encryption can be used for the first time. As long as routing is not activated, the DoIP server ignores all other messages except the routing activation request message. Also unknown source addresses are not accepted and the socket is closed again. While slightly increasing an attacker’s effort, it is easy to spoof source addresses to circumvent this measure.

Optionally, for better protection, the car may require extra measures to accept routing activation from a tester. These include manual user consent, confirming the routing activation in the car cockpit screen to prevent unwanted connections. In this case, to proceed the attacker needs access to the car’s interior [11, DoIP-105]. TLS can also be required by the car for certain diagnostic sessions [11, DoIP-174]. Manual user consent and TLS, both, are very effective measures for mitigating numerous vulnerabilities, which considerably increase the complexity of an attempted attack. Table 1 gives an overview of which vulnerabilities are mitigated by the use of TLS.

Figure 22 in the standard [11] mentions an optional authentication mechanism in the DoIP protocol during the routing activation phase. This authentication mechanism is not specified in detail. The realization is left to the vehicle manufacturers and the standard recommends higher layers for it. Due to the lack of a precise specification, we cannot discuss the effectiveness of the optional authentication. If adequate authentication is required from the client, an attacker cannot activate the routing.

Socket handling is part of the routing activation handler. It checks how many sockets are currently connected and if the source address is already used by another socket. If there is still a socket available and the same source address is not yet registered with another socket, it is registered with the socket. If a new connection is established, a new initial inactivity timer is started for the corresponding source address. When the client does not send a routing activation request message while the timer is running, the socket is closed again. If the client sends a routing activation request message in time, the initial inactivity timer is stopped and the general inactivity timer is started. These two timers provide protection against resource exhaustion attacks. An attacker who occupies sockets must do this actively, otherwise the inactivity timers close the socket again. A single source address can only connect to one socket, so an attacker can only occupy one socket with one source address. However, source addresses are easy to spoof for circumventing this measure.

#### 3.3.2 Vulnerabilities

Source addresses are checked for validity prior to the connection setup during routing activation. If the provided source address is unknown, this information is returned in the response. An attacker is therefore able to scan for valid source addresses to gain knowledge about clients known to the vehicle.

This check is performed before the aforementioned optional authentication and before the connection setup, so even with activated authentication and TLS this information leak is not mitigated. This kind of scanning for source addresses was already possible with the draft version [15]. This vulnerability may be of low criticality since the only information the attacker gains is the address of the tester that currently has requested to connect to the vehicle diagnostic interface at this specific point in time.

The DoIP server can reject the routing if TLS is necessary. This is documented in the requirement DoIP-174 [11]. However, for the routing activation handler this case is not shown in Figure 22 of the DoIP standard [11]. Similar to the vulnerabilities in the vehicle identification phase, this deviation of specifications in the standard can lead to fingerprinting. It is not stated when it should be checked in the handler whether a TLS connection is necessary. This inconsistency is new in the current DoIP version.

If the vehicle requires authorization during the routing activation phase but TLS is not used, an adversary can hijack the TCP connection after the routing activation phase and thus bypass authorization. However, this requires a previously active connection to the vehicle to hijack.

### 3.4 Diagnostic Communication

The diagnostic communication is the phase after the server activated the routing for the client. The four different message types of this phase are the

- diagnostic messages,
- alive check messages,
- power mode information messages, and
- DoIP entity status information messages.

There is no authentication in the diagnostic message handler and, without an encrypted and integrity protected channel, an adversary could try to intercept and modify messages to inject potentially dangerous payload into the vehicle.

#### 3.4.1 Diagnostic messages

The diagnostic message is a message type for routing diagnostic requests to and responses from the vehicle network. Diagnostic messages are confirmed with a positive or negative ACK. As explained in Section 3.1.1, only messages sent by the client are confirmed to prevent NACK storms.

Error messages sent from the DoIP server entity can be used to scan the target addresses in the vehicle. The client can request target addresses and receives an error message if it is not known to the server. The attacker thus gains information about the in-vehicle network. These error messages already existed in the draft version [15].

#### 3.4.2 Alive check message

The alive check message is used to ascertain if a TCP socket is still in use. Two types of vulnerabilities exist in this mechanism:

To exploit the first, the adversary needs to intercept the alive check request messages of the server or the alive check response message of the client. Either way, the server receives no response to its request, thinks the socket is no longer active, and closes it.

Secondly, an attacker has the possibility to send alive check response messages when the client has already disconnected from the server. The server still thinks the socket is in active use and the
socket stays open and remains unavailable for new connections. However, this requires to hijack the TCP session beforehand to keep the channel open and to prevent the TCP teardown. With TLS, both types of attacks are no longer possible, since interception of specific messages and hijacking is not feasible if they are encrypted. The attacks on the alive check messages were already possible in the draft version [15].

3.4.3 Power mode information. The possibility of an unnoticed manipulation of the vehicle’s power mode information response causes the following vulnerability. A denial of service takes place if a test device sends a power mode information request to the connected vehicle and receives a spoofed power mode information response. If the test device is mislead that the vehicle is not ready, the tester does not proceed. In contrast, if the test device is made to believe that the car is ready, although at least one server is not yet ready, diagnostic of the car may fail. Besides these denials of service, a second kind of vulnerability may arise in the latter case. Since, from a functional point of view, it should not be possible that critical diagnostic requests take place if ECUs are not ready, this may cause an unspecified operation state. If this is not handled graciously, the implementation may react in an undesirable way to this non-well specified state the attacker places the protocol in. An unjustified reaction in a normal operation mode may cause even safety impact if no additional precautions to deal with this undefined situation are taken.

With TLS the power mode information’s integrity is protected and the attack is no longer possible. Again, this was also possible in the draft version [15].

3.4.4 DoIP entity status information. The DoIP entity status information message is used to retrieve information about the other DoIP entity in one connection. The response contains information like the entity type, maximum number of concurrent TCP sockets and how many of them are currently open, as well as the maximum data size. The entity type indicates whether it is a DoIP node or a DoIP gateway. The following vulnerability of the status information were already present in the draft version [15] and still are in the current standard.

Message spoofing is possible with all four fields of the response message with the intention to disrupt or prevent the exchange of diagnostic data. Changing the entity type or the information about the sockets may prevent diagnostics from running correctly or at all. If the adversary replaces the maximum data size in the response by a larger number, this can result in the diagnostic message handler of the server discarding the message because it is too large. Protected by TLS, this is impossible and values of the messages cannot be manipulated by an adversary.

3.5 Evaluation of the Results

The vulnerabilities that exist in DoIP, which Table 1 summarizes, can be divided into three main types: Vulnerabilities that (1) leak information about the vehicle network and its DoIP entities, such that lead to (2) gaining illegitimate access, and (3) denials of service. All attacks exploiting vulnerabilities in the DoIP header, the vehicle announcement and vehicle identification phase, and routing activation phase are still possible even with an activated TLS or the optional authentication during routing activation. Attacks on existing diagnostic connections are as diverse and critical as those during the vehicle identification and routing activation phases. However, these attacks can be mitigated by using a secure connection provided by TLS, which prevents interception and manipulation of messages. Activating the optional TLS is an effective countermeasure, since for these attacks the attacker needs to inject valid packets into the channel. However, this mitigation is only sufficient if authentication is used as early as during routing activation and allows only authorized DoIP entities to participate in the communication. Thus, TLS and authentication should be enforced for every diagnostic session. However, this may cause incompatibilities with older versions of the DoIP protocol that did not support TLS and authentication.

Information about the DoIP implementation used by a specific entity can be gained from inconsistencies in the standard’s descriptions. These inconsistencies allow fingerprinting, i.e., an attacker can identify the implementation used, in preparation of an implementation-specific attack. The specification in the standard has been improved since the 2011 draft version, but two major inconsistencies still exist in the current version: One in the sync status specification and one in the TLS activation specification.

We discuss the fulfillment of the security requirements of DoIP, described in Section 2.2. While TLS is now supported by DoIP, its use is not mandatory and DoIP can still be used without any protection. Thus, we discern the security properties of DoIP with and without TLS.

The DoIP protocol specifies to use only the source addresses to determine the origin of data. This is insufficient to provide authenticity and authorized access, since spoofing and connection hijacking vulnerabilities exist for the insecure connection. Without a secure connection, for the lack of any kind of message verification mechanism like signatures, the integrity of the diagnostic data is also unprotected. Likewise, no mechanism in DoIP can determine whether a message is current to prevent replay attacks. Freshness is therefore not guaranteed without a secure connection. Without encryption, the confidentiality in the system is not ensured. The availability is not guaranteed, since denial of service attacks that exploit the lack of integrity protection are possible.

With TLS in use for providing a secure channel, confidentiality, integrity, authenticity, and freshness are gained by the secured channel during the diagnostic communication. The lack of a possibility to use TLS in the earlier protocol phases prevents any improvement of the protection of the communication during these phases. If the client connects via an otherwise secure channel, the authorization in the routing activation phase is sufficient to guarantee authorized access to the vehicle network. Authorization can be gained through mutual authentication of the client and server during TLS connection setup in the routing activation phase. The fine-grained access control to UDS diagnostics must be handled in the application layer.

By its design, no dedicated security measures are built into the DoIP diagnostic communication phase. TLS was added only in the latest version of the standard and was not part of the original protocol design. The design of the vehicle announcement, vehicle identification, and parts of the routing activation phases does not even allow the use of TLS. Furthermore, the existing measures in the vehicle announcement, vehicle identification, and routing activation
phases do not sufficiently mitigate the vulnerabilities, specifically in the absence of the possibility to communicate over any secure channel in these protocol phases. An attacker that can be mitigated by the existing measures, which we described in Section 3.1.1 and Section 3.2.1, has only very limited access to the network and cannot inject arbitrary packets into the network, as a more realistic Dolev-Yao attacker can. Measures with limited effectiveness against denial of service exist for the vehicle announcement and routing activation phases. Only the measures manual user consent and authentication, which both are marked optional in the standard, render sufficient protection against illegitimate access.

4 FORMAL ANALYSIS

In the preceding security analysis, we found vulnerabilities like information leakage and illegitimate access in the protocol, which we confirm in a formal analysis. Errors in the design, such as inconsistent specification in the protocol, cannot be detected using formal analysis since this information cannot be formalized in the proper model.

The Tamarin models are simple, since there are hardly any security measures in the DoIP protocol [11], which can be verified. We check the models for authenticity and secrecy and if they are fulfilled, we conclude that the integrity and confidentiality properties are fulfilled. Preventing the information leakage and illegitimate access vulnerabilities, a secret message is noted in the model with the action fact Secret as shown in Listing 1. If there is no case in which the adversary K knows the message, then the message is confidential. The Tamarin action fact Authentic is used to verify that the message was not sent by the adversary. For each message sent, a Send action fact must be modeled as shown in Listing 2 to check the authenticity.

Availability is not investigated in the models. However, results of the lemma for authenticity allow conclusions about this property. We cannot verify the access control and freshness properties in the Tamarin models because no respective mechanisms are sufficiently defined in DoIP. The Dolev-Yao adversary’s control over the network is modeled with two built-in In and Out rules in Tamarin.

We compare the usage of DoIP with and without TLS but do not verify TLS itself in this work, since it has already formally been analyzed [4, 5]. The TLS-specific key exchange is not represented in the Tamarin models, since Cremers et al. [4] already formally analyzed it with Tamarin. Based on this, we assume for the Tamarin models that TLS provides a perfectly secure communication channel. In case TLS is used, we add an authenticated and encrypted communication channel for DoIP in the analysis where the standard specifies this channel. We model the secure channel in Tamarin using multiset rewriting rules. In total, there are two rules to convert outgoing messages into incoming messages. The two rules tightly link the sender and the receiver to the message [2].

By the properties of the secure channel, neither can an adversary manipulate the DoIP message, nor can they send messages into the secure channel. We model to send a message from A to B by the fact Out_S($A, $B, message). The fact In_S($A, $B, message) represents B’s reception of the message. Consequently, the secure channel of TLS is confidential and authentic [2]. In our analysis, we do not examine the authentication and freshness that TLS provides.

4.1 Vehicle Announcement and Vehicle Identification

In the vehicle announcement phase there are no formalizable security measures, no encryption or signing, present. Our Tamarin models show that messages are not secret, nor are the messages authentic and all vehicle announcement messages are sent as UDP messages to the broadcast address. Everybody, including the adversary in Tamarin, can read them. The Dolev-Yao adversary has full control over the network and can send messages themselves, pretending to be a DoIP entity. The authenticity of the messages cannot be assured.

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### Table 1: Vulnerabilities of the DoIP protocol.

| Vulnerability | Violates         | Target          | Type            | Attacker capability | Section   | Mitigated by TLS |
|---------------|------------------|-----------------|-----------------|---------------------|-----------|------------------|
| Weak protection of version number integrity | integrity       | client + server | downgrade       | inject packet       | 3.1.2     | partly           |
| Missing authentication in vehicle identification | authorization    | client          | illegitimate access | inject packet      | 3.2.2     | no               |
| Inconsistency in sync status       | confidentiality  | server          | fingerprinting  | read from network   | 3.2.2     | no               |
| Spoof failed sync status           | availability     | client          | denial of service | inject packet       | 3.2.2     | no               |
| Scanning for source addresses      | confidentiality  | server          | information leak | inject packet       | 3.3.2     | no               |
| Inconsistency in TLS activation    | confidentiality  | server          | fingerprinting  | read from network   | 3.3.2     | no               |
| TCP hijacking during routing activation | authorization | TCP connection | illegitimate access | inject packet | 3.3.2     | yes              |
| Scanning for target addresses      | confidentiality  | server          | information leak | inject packet       | 3.4.1     | yes              |
| Intercept/inject alive check messages | availability | server          | denial of service | inject packet       | 3.4.2     | yes              |
| Spoofing of power mode information | confidentiality  | server          | illegitimate access | inject packet | 3.4.3     | yes              |
| Spoofing of status information     | availability     | server          | denial of service | inject packet       | 3.4.4     | yes              |

---

Listing 1: Tamarin lemma for the secrecy of a message [2].

```plaintext
lemma secrecy:
"All x #i. Secret(x) @i
== not (Ex #j. K(x)#j)"
```

Listing 2: Tamarin lemma: authenticity of a message [2].

```plaintext
lemma message Authenticity:
"All b m #i. Authentic(b,m) @i
== (Ex #j. Send(b,m) #j & #j<i)"
```
A generic vehicle identification request requires a vehicle to respond to this message with a vehicle identification response. Since this is also sent unencrypted via UDP into the network, anyone can read and modify it, which our Tamarin model recognizes by the failing of the secrecy lemma: Tamarin finds counterexamples. This confirms our assessment from Section 3.2.2, containing multiple vulnerabilities.

### 4.2 Routing Activation phase

A TCP connection is established for routing activation. In this phase, TLS can optionally be used for the first time.

Without TLS there is neither encryption nor authentication, and thus no security measures, in effect and the Tamarin lemmas for message authenticity as well as message secrecy fail. As discussed in Section 3.3.2, this leads to information leakage and illegitimate access vulnerabilities.

With TLS in place, the lemmas on secrecy and authenticity of the messages succeed. Spoofing or eavesdropping of DoIP messages is no longer possible with a secure connection over TLS. This also means that hijacking of connections and bypassing of the authentication in the car is no longer possible. TLS successfully provides confidentiality and integrity for DoIP in this phase. Still, scanning of source addresses is possible with TLS in use.

### 4.3 Diagnostic Communication

When routing is activated, client and server can exchange further messages. A TCP connection, optionally with or without TLS between the tester and the server, can be set up. There is no authentication specified in this protocol phase. The multiple models and message types of this phase are similar to each other.

#### 4.3.1 Diagnostic messages

A client that sends a diagnostic message to the server receives an ACK or a NACK from the server. When transmitting diagnostic data without TLS, there are no security measures that can formally be represented in the model. The lemmas for secrecy and message authenticity fail. Spoofing and eavesdropping of data is possible. This also affects diagnostic data of the higher layers, as long as they do not encrypt their payloads themselves.

If TLS is used, the lemmas succeed, so spoofing of and eavesdropping on messages is impossible. The authentication provided by TLS in the routing activation phase is sufficient to achieve the authentication security property.

#### 4.3.2 Alive check messages

The situation is similar for alive check requests and responses. There are no verifiable security measures except for the optional TLS. If it is not used, the lemmas fail here as well and spoofing and eavesdropping are possible and intercepting messages to produce a subtle denial of service attack is possible.

The use of TLS, and thus the transmission of data in a confidential, integrity-protected, and authenticated channel, prevents eavesdropping, unnoticed interception, and modification of messages. The lemmas for secrecy and authenticity of messages succeed. Adversaries can no longer perform denial of service attacks through the alive check messages. TLS provides the means to ensure the availability property in case of the spoofing vulnerability in this phase described in Section 3.4.2.

#### 4.3.3 Power mode and entity status information

The power mode information and the entity status information also lack any security measures. The lemmas for secrecy and authenticity fail.

With TLS, the lemmas succeed, showing that it can fix the spoofing vulnerability, which is the only existing one for these status messages.

### 4.4 Summary

The formal analysis confirms the results of the security analysis of the DoIP protocol in Section 3. Due to the lack of any formally verifiable security measures, eavesdropping and manipulation of messages is possible without the use of TLS.

In contrast, the lemmas for secrecy and authenticity of messages do not fail with TLS in place. Thus, the Tamarin models show that TLS provides ample security for a protocol that contains no security measures as of itself. Thus, it should be deprecated to omit TLS for DoIP. We discuss further countermeasures in the next section.

### 5 RECOMMENDED COUNTERMEASURES

This chapter presents our proposal for measures to improve the security of the DoIP protocol. The measures are based on the results from Section 3 and the results of the formal analysis in Section 4.

To add any confidentiality, authenticity, and authentication, the use of TLS should be mandatory for DoIP connections over a network. The standard currently allows that the vehicle manufacturer decides if a secure connection is necessary for only certain diagnostic sessions. To improve security for all connections, a secure connection should be chosen by the manufacturer. If used, TLS secures the messages between client DoIP entity and server DoIP entity [11]. According to the standard, DoIP entities should support TLS 1.2 and 1.3. However, only TLS 1.3 provides a state-of-the-art security level. For example, authentication-only ciphers are accepted in DoIP with TLS 1.2. The standard states that these should exclusively be used for debugging and development and should be deactivated for operational communication.

The negotiation of a cipher suite between the entities follows the TLS specification: The client starts with asking for the highest TLS version it supports. The server then responds with the same version or has the option of choosing a different version if it does not support the requested one [11]. Since attacks are known on TLS 1.2 and its cipher suites [17], the vulnerable ones should be removed from the list of supported cipher suites for DoIP. Even better would be to only rely on TLS 1.3.

Using TLS prevents spoofing and eavesdropping of messages. Denial of service attacks based on manipulated or intercepted messages can also be prevented. The use of TLS prevents attacks on the routing activation phase and all subsequent messages during diagnostic communication.

#### 5.1 DoIP Header

In the DoIP header, the inverse protocol version is used as an integrity check to verify that correctly formatted messages are received. Instead of using the inverse protocol number, the standard should use a signature over the complete header. This would then...
cover all bytes of the header, and not only the first two, which we consider a weak kind of check. A signature provides a simple and reliable way to verify that a correct message was received unaltered.

5.2 Vehicle Announcement and Vehicle Identification

The vehicle announcement phase is the most difficult to realize countermeasures for. UDP is used and messages are sent to broadcast addresses, which is why Datagram Transport Layer Security (DTLS) is not an option: While DTLS creates a secure channel for UDP, it does not support broadcasts. A signature as proposed in Section 5.1 would mitigate the synchronization status spoofing and thus is our recommendation. In addition, the ambiguities in the specification need to be fixed.

5.3 Routing Activation Handler

Authentication can be used in the routing activation phase. This authentication is optional and its realization is left to the vehicle manufacturer by the current ISO standard. The standard recommends that authentication should be performed on the application layer. Instead, we argue that an optimal approach would be to use TLS client authentication. Together with TLS, it would significantly improve the security of the system, since it reduces the overall complexity: A confidential, integrity-protected, and mutually authenticated channel is established from the beginning and authorization in the application is based directly on the authentication of TLS without a separate mechanism or additional credentials.

To prevent source address scanning, the sequence of the routing activation handler should be changed. The routing activation handler should first authenticate the client, and only after a successful authentication check whether the source address is known. This would prevent scanning of source addresses and at the same time also fingerprinting of the implementation by an unauthenticated attacker.

5.4 Diagnostic Messages

By using TLS and TLS client authentication, adversaries cannot connect without a valid client certificate and thus cannot enumerate target addresses. As we argue above, the subsequent authorization for diagnostic services would be most elegant if using the already performed TLS client authentication. Spoofing and eavesdropping of messages after the routing activation phase can only be prevented by using a TLS connection. With these two measures, all vulnerabilities in the diagnostic communication phase can be mitigated and all desired security properties in this phase can be achieved.

5.5 Summary

The proposed measures could significantly improve the security of DoIP. Data origin authenticity is satisfied by using TLS and client authentication, so only verified sources can send messages and establish a connection. Still vehicle identification requests and responses can be sent by unauthenticated entities. If we assume an access control is based on the TLS client authentication, the security property authorization is also fulfilled.

While dumb attacks on the availability are always possible on a system under the attacker’s physical control, like destroying, unplugging, or jamming, more subtle attacks on the availability can be prevented. Availability can be improved by an authenticity check for the identification phase. Thus, an adversary could not forge a synchronization message to prevent the entities from connecting. To implement this, the DoIP protocol would have to be modified, creating an incompatibility between versions.

A public key infrastructure (PKI) is required for TLS client authentication and the signatures in the DoIP header of the vehicle announcement, vehicle identification, and routing activation messages that we propose. Since the effort of managing a PKI is already required to activate TLS even with only server certificates, the overhead is reasonable. Access levels that distinguish a common workshop tester with uncritical rights from a development or debugging tester with enhanced rights are part of the service 2916 concept in ISO 14229 [12]. There, the UDS standard describes how a tester can authenticate on application layer towards the vehicle based on a client certificate. We expect that any infrastructure for certificate management including online tester-revocation mechanisms, protected key storage in tamper-resistant hardware, and secure deployment of client certificates for UDS can be used for DoIP instead. Beyond currently existing standard solutions, in the future UDS could then be provided with a delegate of the DoIP certificate to implicitly be authorized on the application layer.

6 CONCLUSION

We analyzed to which extent the DoIP protocol is a secure transport protocol for diagnostic data. Therefore, we performed a comprehensive security assessment, verified by the formal analysis of the security properties of the protocol using Tamarin.

Despite its crucial role in ensuring a secure connection between testers and vehicles, DoIP as of itself is insecure in its current state and vulnerabilities exist. Besides TLS, the currently specified measures against denial of service and spoofing in the standard significantly mitigate attacks of adversaries with only limited access to the network. Because of this, our formal analysis with Tamarin can mainly confirm rather obvious assessments of the security of DoIP. Even if the application layer over DoIP uses its own encryption during diagnostic communication, information leakage from the DoIP protocol as well as denial of service attacks are possible.

A great improvement in the security level, compared to previous versions of the specification and the draft, which were assessed before, poses the addition of encryption and integrity protection using TLS. The secure channel provided by TLS can mitigate all vulnerabilities present in the diagnostic communication phase, but none except one of the vulnerabilities during vehicle identification and routing activation. In the standard, the use of TLS and authentication is optional for the vehicle manufacturer. Consequently, the security of the DoIP protocol is dependent on the respective vehicle manufacturer and the implementation. We therefore propose two additional measures to add to the standard: TLS client authentication and a signature over the DoIP header.

The ISO 13400–2 [11] does not define any authentication procedures. This is left to the higher layers in the OSI model and the vehicle manufacturer. To prevent illegitimate access, even when
using TLS, authentication and authorization is required. Therefore, TLS client authentication should be used to protect the systems from unauthenticated access. On application layer, DTLS could perform an additional, fine-grained authentication mechanism, but a more elegant solution would be to reuse the performed TLS authentication for authorization. The earlier in the protocol phases such an authentication is performed, the more vulnerabilities can be mitigated. The earliest vulnerability in the protocol run that TLS in DoIP’s current specification mitigates is the scanning and enumeration of source addresses during the routing activation.

The remaining vulnerabilities that are not due to inconsistencies in the standard can be mitigated by an integrity protection during the vehicle identification and routing activation phases by a signature over the header. The trust in the keys used for the signature can be established from the same PKI as the one required for TLS, thereby adding no extra effort for key management. This prevents most non-trivial denial-of-service attacks and the one that exploits the synchronization feature during the vehicle announcement phase. Confidentiality is not a relevant security property in this phase and since the functionality requires a multicast, DTLS for a protection on transport layer is infeasible. IPsec as proposed by Kleberger and Olovsson [13] may be an alternative to our proposed signature. However, we argue that it introduces higher complexity and is redundant in later phases due to the existing TLS channel, which was not specified in the standard at the time of Kleberger and Olovsson’s writing.

In addition to secure design, a protocol’s security depends also on the implementation. Vulnerabilities are inevitably introduced in individual implementations. Ambiguities must be removed from the standard to prevent that different implementations can easily be discerned and device fingerprinting becomes possible. When the adversary is able to identify the implementation, they can exploit specific vulnerabilities of this implementation.

We envision that in future work, multiple DoIP protocol implementations could be verified together with TLS in real-world scenarios or in simulations to validate the identified vulnerabilities. It should also be investigated whether there are practical limitations of the use of TLS, TLS client authentication, and signatures that we propose for additional protective measures. This should account for the limited resources of embedded systems and practical challenges, like key distribution, which potentially restrict the use of TLS in DoIP entities.

DoIP was not designed to be a secure protocol from the start. TLS was added only later and mitigates not all vulnerabilities. However, TLS boosts security to such an extent compared to the bare usage of DoIP that it should be mandatory together with its client authentication mechanism. These two measures significantly increase the security of the protocol. For additional protection, our proposed measures would need to be adopted in the DoIP standard first, but they require only small changes to the protocol. They complement the existing optional TLS and authentication measures and mitigate the remaining vulnerabilities in the phases not covered by the current standard’s usage of TLS.

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