Who Killed My Parked Car?

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Abstract

We find that the conventional belief of vehicle cyber attacks and their defenses—attacks are feasible and thus defenses are required only when the vehicle’s ignition is turned on—does not hold. We verify this fact by discovering and applying two new practical and important attacks: battery-drain and Denial-of-Body-control (DoB). The former can drain the vehicle battery while the latter can prevent the owner from starting or even opening/entering his car, when either or both attacks are mounted with the ignition off. We first analyze how operation (e.g., normal, sleep, listen) modes of ECUs are defined in various in-vehicle network standards and how they are implemented in the real world. From this analysis, we discover that an adversary can exploit the wake-up function of in-vehicle networks—which was originally designed for enhanced user experience/convenience (e.g., remote diagnosis, remote temperature control)—as an attack vector. Ironically, a core battery-saving feature in in-vehicle networks makes it easier for an attacker to wake up ECUs and, therefore, mount and succeed in battery-drain and/or DoB attacks. Via extensive experimental evaluations on various real vehicles, we show that by mounting the battery-drain attack, the adversary can increase the average battery consumption by at least 12.57x, drain the car battery within a few hours or days, and therefore immobilize/cripple the vehicle. We also demonstrate the proposed DoB attack on a real vehicle, showing that the attacker can cut off communications between the vehicle and the driver’s key fob by indefinitely shutting down an ECU, thus making the driver unable to start and/or even enter the car.

1 Introduction

Software-driven Electronic Control Units (ECUs) and wireless (Wi-Fi, Bluetooth, Cellular and V2X) connectivities of modern vehicles are proven to be double-edged swords. On the one hand, they have enabled new vehicle applications and services such as remote diagnosis/prognosis and crash avoidance, enhancing safety, mobility, and efficiency. On the other hand, they have introduced more remote surfaces/endpoints and thus vulnerabilities which an adversary can exploit and, in the worst case, control the vehicle remotely [1–4].
Researchers have demonstrated how vulnerabilities in remote (e.g., PassThru, Bluetooth, Cellular) endpoints can be exploited to compromise an ECU and access the in-vehicle network [2, 5]. By exploiting the remotely compromised ECUs, researchers have shown to be able to control vehicle maneuvers or even shut down a vehicle via packet injection in the in-vehicle network [3, 6–8]. The vulnerabilities that were exploited in (remotely) compromising and thus controlling an ECU are, in fact, considered to be inevitable due to the inherent nature of automotive manufacturing: in-vehicle components and software are developed and written by different organizations, and thus vulnerabilities emerge naturally at interface boundaries [2]. Such a reality of vehicle cyber attacks has made vehicle security one of the most critical issues to be addressed by industry, academia, and governments.

While various ways of attacking and thus controlling the vehicle via security vulnerabilities have been proposed and demonstrated, all these attacks are shown to be feasible and effective, only when the vehicle is running. That is, the conventional belief of vehicle cyber attacks and their defenses is that attacks are feasible and their defenses are necessary only while the ignition is on. Thus, there is a lack of understanding of what an adversary can achieve or even whether s/he can mount malicious attacks while the vehicle’s ignition is off.

In this paper, we show such a general belief does not hold since an adversary can attack and control a parked vehicle (i.e., with ignition off) and immobilize it indefinitely. Specifically, we propose two new attacks—battery-drain and Denial-of-Body-control (DoB)—which make the vehicle inoperative. By mounting the battery-drain attack, an adversary first gains access to the in-vehicle network then controls various functions of the car, and finally drains/discharges the battery to a level where the car cannot be started. In this paper, we refer to “immobilize” as an action that prevents the driver from starting or driving the car. As the ignition is off, one might think that no matter what message(s) the attacker injects, none of the in-vehicle ECUs would receive, and respond to, the injected messages. Surprisingly, however, our analyses of various in-vehicle network standards and their protocol implementations reveal the feasibility of controlling ECU functions via message injections even when the ignition is off. Ironically, the main reason for this feasibility is the “wake-up functions”—which are intended to enhance the driver’s experience/convenience—let the adversary wake up ECUs (of a parked vehicle) and then control them. That is, the wake-up functions that were originally designed for a good cause become an attack vector. Wake-up functions are standardized, implemented, and thus provided in various in-vehicle networks so that car manufacturers can provide remote standby functions, such as remote diagnostics, door/temperature control, and anti-theft. Without the wake-up functions, the ECUs providing such functionalities would have to run continuously, hence consuming too much of battery.

Therefore, exploiting such a standardized and thus available wake-up function, the attacker (i) wakes up ECUs by injecting a wake-up message, (ii) controls the awakened ECUs by sending certain messages (e.g., those that turn on lights, unlock/lock the door, change power mode, open trunk, etc.), and therefore, (iii) achieves his goal of draining the vehicle’s battery. In order to control such functions, the attacker must know which messages (more specifically, with which message IDs) to inject, usually requiring some (painstaking) reverse-engineering with fuzzing [2, 3]. However, for the
purpose of battery-drain attack, we propose a driver-context-based scheme, which sig-
nificantly lowers the technical barrier for the adversary to reverse-engineer the required
control messages, i.e., figuring out which message IDs to use, thus helping the attacker
succeed in battery-drain attack.

Through the proposed Denial-of-Body-control (DoB) attack, in addition to simply
waking up ECUs (as was also done in the battery-drain attack), an adversary can force
all awakened ECUs to enter the “bus-off” state, i.e., shut-down. The attacker does this
is to exploit the fact that, depending on their software configuration, some ECUs do
not recover from a bus-off; a policy specified in the ISO 11898-1 standard [9]. We find
through evaluations on real vehicles that a DoB attack can, in fact, lead to a case where
important ECUs, such as a Remote Control Module (RCM)—which is an integral part
of remote key and security functionalities—do not recover from a bus-off, i.e., remain
shut down. As a consequence, the communication between the key-fob and the RCM
(i.e., vehicle) is cut off, thus making the driver unable to enter or start his vehicle.

It is important to mention that the proposed battery-drain and DoB attacks are in-
teresting, critical, and very different from the attacks known to date for the following
reasons.

• One common irony of the two proposed attacks is that the wake-up function of
in-vehicle networks, which was originally standardized, designed, and built for
enhanced user experience/convenience, is exploited as an attack vector. Capital-
izing on the wake-up function, the adversary becomes capable of mounting the
attacks even while the ignition is off.

• The feasibility of, or ease in mounting the attacks stems from the fact that the
wake-up signal/message was defined to be very simple. A simple (agreed-on)
wake-up message (e.g., one 0-bit) facilitates the design of low-power ECUs/transceivers,
thus extending the battery operation time. We refer to “battery operation time”
as how long the battery can last to provide enough power for the driver to start
the car. From a security viewpoint, however, such a battery-saving feature makes
it easier for the attacker to wake up ECUs and then drain the vehicle’s battery.

• The simplicity of the wake-up signal makes message encryption or use of Mes-
 sage Authentication Codes (MAC) (some state-of-the-art defenses) unable to
prevent an attacker from waking up ECUs.

• The number of ECUs that can/must be awakened, tends to increase as more en-
hanced standby features are added to newer vehicle models. This will allow the
attacker to immobilize the newer models far more quickly and easily than the
older ones.

Through extensive experimental evaluations of 11 real vehicles— i.e., 2008–2017
model-year (compact and mid-size) sedans, coupe, crossover, PHEV (Plug-in Hybrid
Electric Vehicle), SUVs, truck, and an electric vehicle—we show that all (except one
2008 model-year) of our test vehicles are equipped with the wake-up functions, render-
ing both battery-drain and DoB attacks feasible. Moreover, we show that by mounting
a battery-drain attack, the adversary can speed up the average battery consumption by
at least 12.57x, drain the car battery within a few hours, and therefore immobilize the vehicle. We also demonstrate the proposed DoB attack on a real vehicle and show that the attacker can shut down an ECU indefinitely and thus prevent the driver from entering or starting the car.

In summary, we make the following main contributions:

1. Showing the feasibility of waking up ECUs via message injections by analyzing in-vehicle network protocols, standards, and implementations, and demonstrating it on 11 different real vehicles;
2. Discovery of two new attacks—battery-drain and DoB attacks—through which an adversary can immobilize vehicles while the ignition is off; and
3. Demonstration of the two newly proposed attacks on a real vehicle.

2 Background

2.1 Terminal Control

The car battery powers in-vehicle ECUs not only when the ignition is on but also when it is off. When and how much battery/power an ECU drains depends on the terminal it is connected to. In the DIN 72552 standard [10], terminals are defined as follows. Connected ECUs attached to

- Terminal 15: switched on with ignition on and (totally) off when ignition is off
- Terminal 30: permanently powered on but usually runs in sleep mode, while the vehicle is parked and locked (i.e., ignition is off).

This definition of differentiation in terminal control is to provide different functionalities in vehicles when the ignition is on/off. As an example, consider the Passive Keyless Entry and Start (PKES) system, which allows users to open and start their cars while keeping their car keys in their pockets [11] and is equipped in most contemporary vehicles. In order to provide the keyless entry feature, the ECU running PKES will have to be connected to terminal 30 and be permanently powered on, continuously sensing whether the owner’s/driver’s key fob is within a certain range. Meanwhile, if the power modes of such permanently powered on ECUs are not properly managed, they will quickly drain the car battery. Thus, to minimize their power consumption, as described in the DIN 72552 standard, they operate in sleep mode in which only their transceiver (not their microcontroller) is powered on. This is for the ECU’s transceiver to still be capable of detecting and therefore responding to any wake-up signals. For this reason, transceivers have a separate power supply [12]. This way, while the ignition is off, ECUs asleep switch to, and operate in normal mode, i.e., wake-up, only when required, thus preventing fast drain of the battery and typically keeping cars continuously parked/idle for 25~40 days without losing battery power. The battery doesn’t get charged by the alternator until the vehicle engine runs back again with the ignition on.
Table 1: Overview of vehicle bus systems with wake-up capability [13]. In all in-vehicle networks, but MOST, ECUs are woken up simultaneously, i.e., a global wake-up, when a wake-up signal is detected on the bus.

| Bus         | Data Rate | Industry Standard                  | Wakeup  |
|-------------|-----------|------------------------------------|---------|
| CAN         | 500 kBit/s| ISO 11898-1                        | Global  |
|             | 125 kBit/s| ISO 11898-2                        | Global  |
|             | 33.3 kBit/s| ISO 11898-3/5                      | Global  |
| LIN         | 19.2 kBit/s| GM LAN                             | Global  |
| SAE J2602   | 10.4 kBit/s| SAE J2602                           | Global  |
| FlexRay     | 10 MBit/s | FlexRay Consortium                  | Global  |
|             | 5 MBit/s  |                                    |         |
|             | 2.5 MBit/s|                                    |         |
| MOST (Multimedia) | 100 MBit/s | MOST Cooperation                   | Global  |
|             | 1 GBit/s  |                                    |         |

2.2 Wake-up

Even when the ignition is off, the need of ECUs asleep to be awakened is increasing for enhanced user/driver experience/convenience. For example, vehicle OEMs are providing useful functions, such as PKES, overnight remote diagnostics, remote temperature control, remote door control, and anti-theft while the vehicle is parked and turned off. We refer to such functionalities that are executable/executed while the ignition is off as standby functions. To meet such a need, ECUs asleep are designed and configured to be awakened via two different mechanisms: local wake-up and bus wake-up.

A local wake-up is triggered when a switch attached to the ECU (e.g., a receiver for the remote key) is turned on. This drives a logic state change on its WAKE pin and thus re-activates the whole ECU. Another mechanism in which an ECU wakes up is whenever it sees a specific in-vehicle network signal, i.e., wake-up message/signal, on the bus. Upon detection of a wake-up signal by the ECU’s transceiver, which remains ON even while the ignition is off, it turns on the power supply of the ECU, thus waking up the whole ECU, i.e., enters normal operational mode. We will later elaborate on what the wake-up signals are when we discuss the proposed attack methods. If no additional wake-up signal is received within a certain (preset) period, the ECU returns to sleep mode.

Table 1 summarizes in-vehicle network standards/protocols that define such a wake-up functionality/capability of providing a pathway for driver-friendly applications. One can see that it is standardized, implemented, and used not only in CAN—the de facto standard of in-vehicle networks—but also in all other in-vehicle networks, except for MOST. However, for the purpose of more in-depth discussion, we focus on CAN when discussing the two proposed attacks.

CAN ECUs/transceivers with such a wake-up feature (i.e., wake-up detection module) have been in the market for more than 15 years (as of 2017) [15]. Fig. 1 shows a block diagram of a Texas Instrument (TI) SN65HVD1040 transceiver implemented
Figure 1: *TI SN65HVD1040 transceiver* [14]. The bus monitor module continuously checks whether or not there are any wake-up signals on the bus. If so, it wakes up the whole ECU.

with a bus monitor module for the wake-up function. We found that (almost) all CAN transceivers from other manufacturers also have such a wake-up detection module with different names like wake-up detector, wake-up filter, etc.

3 Adversary Model

We consider an adversary whose objective is to *immobilize* the victim’s vehicle while the ignition is off, and stay as *stealthy* as possible during, and even after the attack. By immobilizing the vehicle, i.e., compromising its availability, s/he prevents the driver from starting or driving the car, making the vehicle unavailable when the driver/owner wants or needs to use it. In order to be as stealthy as possible during, and even after the attack, the adversary also aims to immobilize the car before the driver attempts to enter/start it. Therefore, although an adversary may in fact immobilize a vehicle by simply flooding the in-vehicle network when the driver attempts to start it—which, in turn, prevents any other ECUs (e.g., Body Control Module) from receiving/processing commands—or by jamming the key-fob wireless channel, we do not consider such an adversary. Immobilizing the vehicle in such ways is likely to expose the attacker, since the driver/owner would be in the vicinity of the car when the attack is mounted. In contrast, by immobilizing the vehicle before the driver attempts to enter/start it, the adversary won’t leave any trace at all, except the immobilized vehicle, i.e., very stealthy.

As in previously discussed attacks [2, 3, 5, 7], we consider the adversary capable of remotely (but not physically) compromising an in-vehicle ECU via numerous attack surfaces and means, and can thus gain its control; physically compromising an ECU requires physical access and thus is not stealthy. That is, the adversary can compromise 1) a (third-party) OBD-II (On-Board Diagnostics) dongle/device in advance, and gain
remote control of the vehicle once the driver plugs it in to his/her car (as demonstrated in [16])\(^1\) or 2) an in-vehicle ECU (e.g., telematic unit which has external connectivities), remotely, so as to access the in-vehicle network [2, 5]. Since such an adversary would have access to the vehicle’s CAN bus, we call such an adversary a CAN attacker. Once an ECU is compromised, we consider the CAN adversary to be capable of performing at least the following malicious actions. The adversary can inject any message with forged ID, DLC (Data Length Code), and data—which we refer to as attack messages—on the bus as they are managed at user level. Also, since CAN is a broadcast bus, the adversary can sniff messages on CAN. These are the basic capabilities of a CAN adversary who has the control of a compromised ECU. The practicability of such an adversary model has already been proved and demonstrated in [2, 7, 8].

4 Immobilizing a Vehicle

We now introduce two new attacks through which a CAN adversary can immobilize the victim’s vehicle while the ignition is off, i.e., compromise the vehicle’s availability while it is parked and turned off.

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\(^1\)Once it is plugged in, we can consider the OBD-II dongle/device as an in-vehicle ECU.
4.1 High-level Overview of the Proposed Attacks

Through a compromised in-vehicle ECU (e.g., telematic unit, OBD-II dongle), the CAN adversary has access to the CAN bus irrespective of whether the ignition is on or off. However, especially when the ignition is off and thus all ECUs are asleep or turned off (until the ignition is turned on again), an attack message injected by the adversary may not be delivered to those ECUs. That is, no matter what messages the adversary may inject, these ECUs may not respond.

Fig. 2 shows an overview of how the CAN adversary immobilizes a vehicle in such a case. In order to control/attack ECUs on the bus, s/he first wakes them up and then immobilizes/cripples the vehicle via a battery-drain or DoB attack. In the case of battery-drain attack (Section 4.3), the adversary will attempt to exploit the awakened ECUs for controlling certain functionalities of the vehicle (e.g., illuminating exterior/interior lights) and thus draining its battery. In order to figure out which message ID to use for such a control, the attacker goes through a message reverse-engineering process based on driver context, which will be detailed in Section 4.3.3. That way of reverse-engineering messages allows the attacker to succeed in battery-drain attack much easier than via conventional reverse-engineering such as fuzzing. In case of DoB attack (Section 4.4), the attacker need not go through the reverse-engineering process, because the DoB attack does not control ECUs but shuts them down by exploiting their error handling and recovery mechanisms. By mounting a battery-drain and/or a DoB attack, the attacker immobilizes the vehicle.

4.2 Waking Up ECUs

When the ignition is off, some ECUs are configured to run in sleep mode and continuously monitor if there is any incoming local or bus wake-up signal. Taking this into consideration, using his/her compromised ECU, the CAN adversary attempts to wake up all other ECUs by delivering a bus wake-up signal to them. Then, what type of bus wake-up signal should the adversary use in order to wake up the ECUs?

**Standardized wake-up signal.** The remote wake-up behavior of a CAN ECU was first introduced and specified in the ISO 11898-5:2007 standard which defines the bus wake-up behavior as:

“One or multiple consecutive dominant (0-bit) bus levels for at least $t_{\text{Filter}}$, each of them separated by a recessive (1-bit) bus level, trigger a bus wake-up.”

The ISO standard specifies $t_{\text{Filter}}$ to be within [500ns, 5µs]. We can thus deduce the following three facts:

S1. Dominant bus level (i.e., bus with 0-bits) for longer than 5µs causes a wake-up;

S2. Dominant bus level for shorter than 500ns is ignored; and

S3. Dominant bus level for a period between 500ns and 5µs may cause a wake-up.

The actual value of $t_{\text{Filter}}$ depends on the transceiver being used. In a CAN bus with bit rates up to 200 kBit/s, i.e., bit width longer than 5µs, the dominant bus level condition S1 is met with any 0-bit within a CAN frame/message. For bit rates up to 500 kBit/s, the
dominant condition $S_1$ is also met for any normal CAN data message since its 1) RTR, 2) IDE, and 3) $r_0$ bit (ISO11898-1:2003) (later revised to an FDF bit in ISO11898-1:2015) are all defined to be dominant (0s) as shown in Fig. 3. That is, in a 500 kBit/s bus, since those three bits—each with width 2µs—are sent consecutively, the resulting duration of dominant bus level becomes at least 6 µs, thus (automatically) guaranteeing/satisfying $S_1$ to be met.

Note that the ISO standard specifies such dominant bus levels to be separated by a recessive bus level. This is easy to achieve since CAN always 1) stuffs a recessive 1-bit after 5 consecutive 0 bits, i.e., bit-stuffing [3, 17], 2) has certain fields fixed with a 1-bit (e.g., CRC delimiter, ACK delimiter as shown in Fig. 3), and 3) the user can determine what value(s) to fill in such fields as ID, DLC, and DATA. The same also applies to the extended CAN format which has a 29-bit ID. However, in this paper, we only consider the basic/standard CAN data format since the extended format is seldom used (due to its bandwidth waste) in contemporary vehicles; most vehicles use the basic/standard format with 11-bit IDs.

The reason for OEMs’ agreement on a standardized wake-up signal was to guarantee a 100ms link acquisition time [12]. More importantly, the the wake-up signal was defined to be simple to allow for a low-power design (e.g., RC-circuit) of wake-up detection, i.e., an energy-efficient sleep mode [12]. OEMs want to reduce the average standby/asleep current consumption to be less than 300µA per ECU, and many of them reduce it even further down to less than 100µA [18]. That is, the simple design/definition of a wake-up signal was to prolong the battery operation time, i.e., energy-efficient.2

Similarly to CAN, other in-vehicle networks such as FlexRay and LIN define the wake-up signals to be simple for energy-efficiency. FlexRay specifies the signal to be long high/low [12] and LIN specifies it to be a dominant bus level within the interval [250µs, 5ms] [19]. The wake-up signal in those networks also wakes up all ECUs asleep on the bus; see Table 1. An adversary can, therefore, easily wake up ECUs while the ignition is off, in not only CAN bus but also other in-vehicle networks. However, in this paper, we focus on CAN for a more in-depth treatment of the attacks.

**CAN adversary waking up the bus.** As the wake-up signal is simple and standardized, all the CAN adversary needs to do is inject a fabricated *wake-up message/signal* into the bus, which s/he has access to. As mentioned earlier, due to its simple definition,

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2 Energy-efficiency of vehicles is no longer an option, but is a prerequisite when defining and developing new ECUs. From 2020 onwards, there will be a very challenging threshold for CO$_2$ emissions with 95g CO$_2$/km for passenger cars sold in Europe [13].
a wake-up message with *any* content (i.e., ID, DLC, and DATA which are controllable by a remote attacker) will wake up ECUs. Note, however, that only those ECUs which are asleep (i.e., not completely off) will be awakened. This is ironic/paradoxical since wake-up signals are made simple for energy-efficiency, i.e., to minimize battery consumption, but such a simple design helps the attacker wake up ECUs, thus making the vehicle *less* energy-efficient.

**Power source of the adversary’s ECU.** One remaining requirement for a CAN adversary to achieve this is that his (compromised) ECU has to remain powered on. The attacker achieves this fairly easily thanks to two interesting facts.

First, the ECUs which a CAN adversary would (or can) compromise and thus use are most likely to be continuously powered on, or (at least) have a separate power source/supply during their operation. A typical example ECU that an attacker would target (to compromise) is the telematic unit due to its wide variety of external/wireless connectivities. The practicability of the telematic unit being compromised has already been demonstrated in [2, 7, 8]. Interestingly, the telematic unit—which is regarded as one of the most vulnerable ECUs [2, 3, 16, 20]—is usually completely (or at least periodically) powered on so as to respond to external events (e.g., requests for remote diagnosis, remote door/temperature control, anti-theft) even after the ignition key has been taken out [21]. Moreover, a telematic unit is usually equipped with an alternative power supply so that it can operate even when the car battery or electrical system is faulty [22]. Similarly, an OBD-II device/dongle, which is also a good target for an adversary to compromise (as demonstrated in [2, 16]), can also be completely powered on (by the attacker) since it is also normally equipped with an external power source (e.g., battery). In summary, ECUs which a CAN adversary will likely compromise via their exposed attack vectors are the ones which are completely/always powered on either by the car battery or their own power supplies.

Second, although the operational mode of a (compromised) ECU is preset to run in sleep mode when the ignition is off, it does not restrict the adversary to change such a setting. Two most common CAN controllers—Microchip MCP2515 and NXP SJA1000—both allow modification of their operation mode (e.g., normal, sleep, listen-only) through software commands [23, 24]. For ECUs with the Microchip MCP2515 CAN controller, the Serial Peripheral Interface (SPI) remains active even when the
MCP2515 is in sleep mode, thus allowing access to all registers. Thus, through the SPI, it is also possible for the user/adversary to read/write the CAN controller registers, including the operational mode register [23]. Such user-level features for configuring the CAN controller allow attackers to easily switch from sleep to normal mode via software commands.

As a result, a CAN adversary can inject wake-up messages to the CAN bus while the ignition is off. The transceivers of ECUs asleep observe a wake-up signal on the bus, switch on the ECUs’ power supply (usually via an interrupt), and boot up the microcontroller. Hence, the ECUs return to normal operational mode. Since CAN is a broadcast bus, even a single injected message from the CAN adversary causes all ECUs asleep to run in that mode.

4.3 Battery-Drain Attack

We now give a detailed account of how an adversary can drain the battery of a vehicle via message injections, i.e., mount a battery-drain attack. Here, we only give the details of how the battery-drain attack can be mounted. Section 5 will detail their consequences via in-depth evaluations on real vehicles.

4.3.1 Attack 1 — Waking up ECUs

While the ignition is off, the CAN adversary can first attempt to wake up ECUs via message injections. Once the ECUs asleep wake up, they switch to, and run in normal operational mode. Note, however, that an awakened ECU goes back to sleep after a certain period of time (configured by the OEM). Hence, by waking up ECUs as much and as frequently as possible, the adversary can continuously force those ECUs to run in normal mode, although they should remain asleep. If ECUs are configured to stay in normal mode (after waking up) for a duration of $T_{\text{wakeup}}$, the frequency of wake-up messages from the attacker has to be at least $\frac{1}{T_{\text{wakeup}}}$. Since the adversary can read/sniff messages on the CAN bus, s/he can easily infer $T_{\text{wakeup}}$ from the monitored traffic.

With continuous injections of wake-up messages, ECUs (that would usually be asleep) will be forced to stay up in normal mode and thus draw much more current (i.e., power) from the battery. In contrast to the ECUs asleep, which normally consume less than 100µA of the battery current, normal-mode ECUs consume several mA. Therefore, by simply waking up ECUs—the simplest battery-drain attack—the CAN adversary can significantly increase the battery current consumption and can thus reduce the battery operation time. We will later in Section 5 detail the amount of current drained by simply waking up ECUs, and how that affects the vehicle battery operation time.

4.3.2 Attack 2 — Controlling ECUs

An interesting consequence of waking up ECUs is not only the increased battery current consumption but also the pathway it provides for the attacker to control ECUs. After waking up, since ECUs previously asleep now run in normal operational mode—the same as when the ignition is on—the CAN adversary becomes capable of controlling
them. We refer to “controlling an ECU” as executing the ECU’s function(s) via message injections. For example, an attacker may inject an attack message with ID=0x11, which is usually sent by some other ECU. If message 0x11 is processed and used by the brake ECU in engaging/disengaging the brake, an injection of 0x11 will control that ECU’s brake function and thus the corresponding vehicle maneuver.

However, the criticality levels of some (malicious) controls would be different from when the vehicle’s ignition is on and moving, compared to the case when the vehicle is parked with its ignition off, i.e., different from existing attacks. For example, ensuring that the brakes do not unwillingly engage/disengage in a moving vehicle is safety-critical. It might not be critical when the ignition is off and the vehicle is parked. From the battery/energy consumption perspective, the controls that would be considered malicious are different.

Controls that increase battery consumption. Since the activation of interior/exterior lights is one of the highest battery-consuming functionalities, the adversary can attempt to control them to increase the battery current drain. Instead of attempting to directly control the interior/exterior lights (via light-control messages), we exploit the following vehicle functions which indirectly illuminate various lights inside and outside the vehicle.

C1. Changing the vehicle’s power mode;
C2. Repeatedly unlocking and locking doors; and
C3. Opening the trunk.

The reason why we exploit such indirect functions is that their control messages are far easier to reverse-engineer (i.e., figure out the meaning/purpose of messages) than the direct (light-)control messages if done based on driver context. This fact counters the common belief that reverse-engineering CAN messages is a non-trivial painstaking process [3]. We will later in Section 4.3.3 detail how the message reverse-engineering process can be eased, especially for the purpose of battery-drain attack.

C1. Changing the vehicle’s power mode. Depending on the ignition switch position, vehicles run in different power modes such as off, accessory mode, run, and start. An adversary exploits this fact and can first reverse-engineer the control message (via driver context) which determines/reflects the vehicle’s power mode, wakes up ECUs on the bus, and attempts to change the power mode using the reverse-engineered message/ID.

Fig. 4 shows why changing the power mode of a vehicle can be considered as an indirect way of illuminating lights and thus increasing the battery consumption, i.e., mount a battery-drain attack. It shows what happened when we tried to alter the power mode of one of our test vehicles via message injections. Here, every procedure and consequence was executed and happened while the ignition was off. We will later in Section 5 provide the evaluation settings and general methodologies in accessing the CAN bus and injecting messages. Note that it was fairly easy to reverse-engineer (or figure out) the power-mode control message, especially when using the context—a

3To control vehicle functions, we must know which message ID(s) to use/inject. However, since that information is OEM-proprietary, we must reverse-engineer them.
main reason why we attempted to mount the battery-drain attack via power-mode control instead of (direct) light control. When we controlled the power mode of a parked vehicle, as shown in Fig. 4, various indicators on the dashboard were (temporarily) illuminated. Similarly, albeit not shown in Fig. 4, the infotainment system was also booted up. When we periodically injected the reverse-engineered “power-mode control” message to the bus, the indicators on the dashboard continuously flickered and the infotainment system was intermittently turned on.

Although the vehicle ignition was off, the injection of a (fabricated) power-mode control message was successful since the vehicles’ power-mode master is the Body Control Module (BCM)—the ECU which has to be at least asleep (but never completely off) due to its important role in providing various standby functions. BCM not only plays a central role in a car by maintaining control over its various functions such as power windows, air conditioning, and central locking, but also governs security functions including Remote Keyless Entry (RKE), Vehicle Anti-Theft Security System (VTSS), and Passive Anti-Theft System (PATS).

In summary, if a CAN adversary not only wakes up ECUs but also reverse-engineers and injects power-control messages, s/he can continuously illuminate various lights/indicators and further increase the overall battery consumption: an enhancement of battery-drain attack that simply wakes up ECUs.

C2. Unlocking and locking the door. In addition to the previous two types of battery-drain attack — waking up ECUs and controlling the power mode—a CAN adversary can also attempt to repeatedly unlock and lock the vehicle (while parked). The reason why a CAN adversary would mount a battery-drain attack in this way is not only 1) the unlock/lock messages are easy to reverse-engineer but also 2) it activates various light functions. When the driver (or the adversary) unlocks the car, welcome lights of the vehicle illuminate for an enhanced visibility for the driver. Note that the numbers and types of the welcome lights that illuminate may vary with the vehicle manufacturer/year/model, and also depending on whether the lighting control system is set as “automatic,” which is the default setting for most drivers [2].

During daytime, lights such as marker lights, interior lights, exterior footlights (on side mirrors), and coming-home lights will/might illuminate when the driver unlocks the vehicle. At night time, the vehicle will turn on its headlights. By reverse-engineering and injecting “door lock control” messages to the bus and then exploiting these driver-friendly lighting controls, an adversary can continuously illuminate all the welcome lights and thus significantly increase the average battery consumption; another enhancement of battery-drain attack. Similarly to the attack case C1 where the power mode was controlled, the door control module is another ECU which has to provide a standby function such as keyless entry and must thus be not completely off (i.e., must be asleep instead). This allows the attacker to control the door locks even when the ignition is off.

C3. Opening the trunk. The adversary can also attempt to open the trunk of a car similarly to the attack cases C1 and C2. Again, the trunk control module/ECU is another ECU that would have to be asleep, not completely turned off. Therefore, by reverse-engineering the trunk control message, an adversary can (remotely) open the trunk. When the trunk is opened, for enhanced visibility for the driver, (almost all) vehicles are configured to illuminate its interior map, dome, and trunk lights. Again, thanks
Figure 5: *Driver-context-based reverse-engineering.* Using this approach, a CAN adversary can easily figure out which message IDs to use in mounting the battery-drain attack.

to such user-friendly lightings, the adversary can illuminate more lights inside/outside the vehicle and thus further increase the battery consumption, i.e., reduce the battery operation time.

In contrast to C1 and C2, the attacker is only required to inject a single trunk-control message into the bus if the lights remain on while the trunk is open (as some vehicles do). Even if the lights automatically go off after some time, the attacker can re-inject the trunk-control message to re-illuminate them. Note, however, that opening the trunk could be a bit (visibly) intrusive, which is a limitation of this approach, although for some vehicles we observed that it is not. However, if the adversary can deplete the battery before the driver/passenger notices and thus attempts to close it, such an intrusive approach will still succeed in immobilizing the vehicle. When mounted overnight, since the driver/passenger would notice this only when s/he attempts to start the car in the following morning, the attacker could be given approximately half a day or even a few days (e.g., weekends) in succeeding it!

### 4.3.3 Driver-Context-Based Reverse-Engineering

In controlling an ECU (as in C1–C3), since the message IDs that have to be used are different for different vehicle manufacturers and models, adversaries would have to reverse-engineer messages for each vehicle that it targets. This fact generally becomes a (high) technical barrier for the adversary, especially when mounting state-of-the-art attacks on different vehicles. However, for the purpose of battery-drain attack, the message reverse-engineering can be achieved very differently, i.e., not via fuzzing. Specifically, by reverse-engineering messages based on the *driver-context*, it becomes much easier for the adversary to figure out which messages to use in mounting and thus succeeding in battery-drain attack on different/ various vehicles.

The proposed driver-context-based reverse-engineering works as follows.

1. When the ignition is off, the CAN adversary continuously wakes up ECUs and
records/logs the CAN traffic as $\Omega_{off}$ as illustrated in Fig 5. If the adversary knows when the driver usually starts the car (e.g., 9am in the morning), s/he can start such a process just before that time. We define the sets of distinct IDs sent while the ignition is on and off as $S_{on}$ and $S_{off}$, respectively. Then, once ECUs are awakened via a wake-up message from the adversary, $|S_{off}|$ distinct message IDs would be observed on the bus and that number would be lower than $|S_{on}|$, since the number of ECUs running in normal operation mode (and thus periodically sending messages) would be less.

2. The CAN adversary continuously logs the CAN traffic as $\Omega_{off}$ and marks the bit positions of messages’ ($\in S_{off}$) data fields that continuously change as $\Delta_{off}$. One example of $\Delta_{off}$ can be the last byte of the data field where OEMs usually put their 1-byte checksum of each message (ID) [3, 5].

3. When the CAN adversary finds that the ignition is (now) turned on, onwards, s/he records/logs the traffic (of an “ignition on” vehicle) as $\Omega_{on}$. The CAN adversary can acknowledge this by observing a suddenly-increased number of distinct message IDs—from $|S_{off}|$ to $|S_{on}|$—on the bus.

4. Since $S_{off} \subset S_{on}$, the CAN adversary analyzes how the data values/fields, excluding $\Delta_{off}$, of those message IDs ($\in S_{off}$) changed during the period of just before to right after the ignition being started.

An interesting yet important fact about $S_{off}$’s data values (excluding those in $\Delta_{off}$) is that they reflect the driver’s actions before driving the vehicle. Imagine a person who tries to start and drive his/her car. S/he would first unlock the vehicle and then change its power mode, i.e., turn on the ignition. Perhaps, s/he might even open the trunk to put items there before starting the vehicle. Such a routine of accessing and starting the vehicle, which we define as the driver context, is embedded/reflected in $\Omega_{off}$, i.e., the CAN traffic obtained while the ignition was off. Specifically, when the driver makes some action (e.g., unlock the door) while the ignition is off, the data value of an ID ($\in S_{off}$) would change. Note that such a change would not incur in any of the data fields in $\Delta_{off}$, i.e., the bit positions which their values normally continuously change, since the driver’s action and thus the corresponding change in the data values are “temporary”. So, by observing the temporary data changes in $S_{off}$ incurred right before the ignition is turned on, the CAN adversary can easily figure out which messages relate to those driver-context-related controls. Interestingly (and luckily for the CAN adversary), as discussed in Section 4.3, such driver-context-related controls lead to illuminating various indicators/lights. As a result, especially for a CAN adversary attempting to mount a battery-drain attack, reverse-engineering the required control messages (e.g., door lock/unlock, changing power modes) becomes far more easier! The same can be applied when the driver stops and leaves the vehicle, since s/he would again change the power mode, perhaps open the trunk, and of course, lock the vehicle.

Given below is an example of how we reverse-engineered one of our test vehicle’s door-control messages. When describing the procedures, we do not use the actual ID value nor the bit positions, since they are proprietary to the OEMs. When comparing two sets of $\Omega_{off}$, one before pressing a remote key fob and another during it, we found
(a) Messages were injected to the parked test vehicle through the OBD-II port.

(b) Vehicle architecture of one of our test vehicles. Once a wake-up message was injected, several ECUs were awakened.

Figure 6: Analysis of how our test vehicle responded to a wake-up message. We established connection to our test vehicle’s CAN bus through the OBD-II port and examined which and how many ECUs woke up when a wake-up message was injected.

that the data fields of message ID=0x01 had changed from [00 10 00 00 FF 00 AB CD] temporarily to [00 30 00 00 FF 00 BC EF]. We verified in advance that the last 2 bytes of message 0x01 continuously change, even without any actions taken on the vehicle. That is, we verified that the last two data bytes of 0x01 belong to $\Delta_{off}$. As a result, we were able to easily figure out that the second byte of message 0x01 controls our test vehicle’s lock and unlock functions. We will later show through evaluations that such an approach was indeed successful and thus let us easily unlock & lock the car, illuminate the welcome lights, and therefore, mount the battery-drain attack.

4.4 Denial-of-Body-control (DoB) Attack

In addition to the battery-drain attack, the CAN adversary can mount a Denial-of-Body-control (DoB) attack in order to immobilize a vehicle, i.e., compromise its availability.

Bus-off recovery. Error handling is built in the CAN protocol and is important for its fault-tolerance. It aims to detect errors in CAN frames and enables ECUs to take appropriate actions, such as discarding a frame, retransmitting a frame, and raising error flags. If an ECU experiences or incurs continuous errors while transmitting or receiving a message, the CAN protocol specifies that its Transmit Error Counter (TEC) or Receive Error Counters (REC) should be increased, respectively [17]. If its TEC exceeds a pre-defined threshold of 255 due to continuous errors, the ECU is forced to enter a state called bus-off and shut down.

Exploiting such a standardized CAN feature, Cho and Shin [3] proposed a new attack called the bus-off attack, which enforces other healthy/uncompromised ECUs to shut down. See [3] for more details of the bus-off attack. The proposed DoB attack is mounted in a similar way to the bus-off attack, except that it further exploits the following fact specified in the ISO 11898-1 standard [9] and thus immobilizes the vehicle. The standard specifies that
“A node can start the recovery from the bus-off state only upon a user’s request.”

where the user’s request depends on the ECU’s software/policy configuration. The proposed DoB attack thus exploits such a definition of bus-off recovery as follows.

While the ignition is off, the CAN adversary wakes up ECUs so as to make them responsive to his injected messages. Then, the adversary switches its bit rate (e.g., from 500 kBits/s to 250 kBits/s). According to the CAN error-handling scheme, this makes all awakened ECUs on the bus continuously experience and incur errors, and therefore enter the bus-off state, i.e., shut-down. This way, the adversary not only mounts the bus-off attack on a targeted ECU (as demonstrated in [3]) but also on all ECUs on the bus. Instead of changing the bit rates, changing internal/net resistances or capacitances can be an alternative method in achieving this. As a result, per bus-off recovery specification, depending on the ECUs’ software configurations, some ECUs would recover from the bus-off state, whereas some will not, i.e., remain shut down.

Depending on the car manufacturer and year/model, ECUs such as BCM or RCM, which is the security ECU that authenticates each message to and from the remote key fob, can in fact be configured/defined not to recover from the bus-off state, mainly for safety, since the bus-off is a serious problem [3], or for anti-theft purposes. Hence, if the CAN adversary were to mount the DoB attack on such a vehicle, then s/he can indefinitely shut down the BCM or RCM, and thus cut off the communication between the (driver’s) remote key fob and the vehicle. Contemporary/newer vehicles are mostly equipped with the PKES system, which allows users to open and start their cars while having their key fobs in their pockets [11] and is installed either in BCM or RCM. For the vehicle to be opened/started, PKES must verify that the legitimate key fob is in the vehicle’s vicinity. Therefore, shutting down BCM/RCM (and thus PKES) would mean that the vehicle will not be able to receive and authenticate any remote key signals (sent by the key fob), thus preventing opening or starting the vehicle, i.e., the CAN adversary immobilizes the vehicle via a DoB attack.

Once the attacker succeeds in mounting DoB attack, there is no need for the attacker to mount the attack, again; some ECUs that have entered bus-off will never boot up again, anyway. This allows the attacker to not only succeed in mounting the attack in a very short period of time but also leave without any trace, i.e., stealthy, except the immobilized vehicle! We will later show through evaluations that such a configuration of BCM/RCM not recovering from bus-off actually exists in real vehicles and thus makes the driver unable to open the door/trunk and start the vehicle even with his/her legitimate, perfectly-functioning key fob.

5 Evaluation

We now evaluate the feasibility and criticality of the two proposed attacks—battery-drain and DoB attacks—on various real vehicles.

5.1 Waking Up ECUs

To verify whether ECUs in real vehicles can indeed be awakened via simple wake-up messages while the ignition is off, we connected a Vector CAN device to our test ve-
Figure 7: Verifying wake-up messages in 11 different vehicles. We compared how many distinct message IDs were observed when the ignition was off but the ECUs were awakened via a wake-up message and when the ignition was on.

Vehicles’ OBD-II port as shown in Fig. 6a.4 We then injected wake-up messages/signals to the CAN bus. The wake-up message we used had its ID, DLC, and DATA fields — that a user/adversary can control at the application layer — all filled with 1s. This was to verify that messages with the minimum number of 0s can also properly function as a valid wake-up message.

In-depth analysis on a test vehicle. Fig. 6b shows the in-vehicle network architecture of one of our test vehicles — a 2017 year model5 — and the ECUs that responded to the wake-up signals/messages. Note that this network architecture of the test vehicle is not unique for the OEM of our test vehicle but is general/valid for the vehicles built by other OEMs; there are only slight variations in the network architecture [25]. We verified which ECUs were awakened by logging the CAN traffic that contains the message IDs observed on the bus, and by mapping those IDs to the corresponding transmitter ECUs using the test vehicle OEM’s CAN Data Base Container (DBC). The CAN DBC describes the properties of the CAN network, the ECUs connected to the bus, and the CAN messages and signals. For the purpose of this research, the CAN DBC file was provided by the test vehicle’s OEM.6

When the wake-up message/signal was injected, one can see from Fig. 6b that not all ECUs were awakened. This would be most probably due to different ECUs being attached to different terminals (with different terminal control policies) in order to minimize battery/power consumption and, at the same time, provide various standby functions. In CAN-1 which connects ECUs performing safety-critical functions, only 4 of 13 of them were awakened. On the other hand, in the CAN-2 bus where ECUs responsible for vehicle body control were connected, almost all ECUs but two were awakened. Considering the fact that contemporary/newer vehicles provide various standby “body control” functions such as keyless entry, hands free (foot) trunk opening, and anti-theft,

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4The OBD-II port can be used to access all CAN buses in a vehicle and is thus the principal means service technicians use to diagnose and update individual ECUs [2].
5The model identity is not revealed for the OEM’s confidentiality.
6Due to its proprietary information, such DBC files are not shared without permission from the OEMs and their suppliers.
Attacks | Discharged Current [mA] | Amplification Factor | Max. Battery Operation Time [Days] |
--- | --- | --- | --- |
None | 12.2 | Baseline | 30.7 |
+ Wake-up | 42.0 | x3.44 | 8.92 |
+ Change Power Mode | 74.5 | x6.11 | 5.02 |
+ Lock & Unlock Door | 101.1 | x8.29 | 3.70 |
+ Open Trunk | 153.3 | x12.57 | 2.44 |

Table 2: Maximum battery operation time under different battery-drain attacks. Based on the measured battery current consumption for each attack, we determined what the (theoretical) maximum battery operation time could be. Note, however, that in reality, the actual operation time would be much lower than these due to the Peukert’s law [26].

more number of ECUs being awakened in CAN-2, i.e., bus with body-control ECUs, than CAN-1 would be the norm.

**Verifying wake-up functionality in various vehicles.** Using the OBD-II device, we also verified how different vehicles (OEMs/years/models) react to the injection of a wake-up message. To confirm that the wake-up functionality exists in different cars, we chose various types of test vehicles: (compact and mid-size) sedans, coupe, crossover, PHEV, SUVs, truck, and an electric vehicle with model-years 2008–2017.

Fig. 7 shows how many distinct messages were observed on the CAN bus 1) when the ignition was on and 2) when we woke up ECUs on the bus via a wake-up message injection while the ignition was off. Since the feasibility of wake-up stems from how the in-vehicle network standard is specified and thus implemented, i.e., instead of OEMs’ design decisions, we have chosen not to identify/reveal the particular make and model used in our evaluation. Note, however, that the 11 examined test vehicles (shown in Fig. 7) are from different OEMs and also represent different models. For some vehicles, since their OBD-II pinout was configured to not provide full access to all of their buses, we only show those that were awakened in the accessible bus(es).

When waking up ECUs in some old cars (most with low-level trims), far less distinct message IDs and lower percentages of them (compared to the case with the ignition on) were observed on the bus than other newer cars. Since the number of ECUs is proportional to the number of distinct message IDs—although it is not linearly proportional—we can infer that there were less awakened ECUs transmitting them in older cars; not all messages can be sent by a single ECU due to the overhead. This would most probably be due to the fact that the older cars do not require/provide any (or not many) standby functions (e.g., PKES). For example, no standby functions (e.g., keyless entry, hands-free trunk opening) were provided in the 2008 and 2013 model-year test cars; the reason why none and only one ECU was awakened, when a wake-up message was injected on the bus.

On the other hand, when we injected a wake-up message on the buses of nine 2015–2017 model-year test vehicles, we observed that 49.12–94.95% (75.44% on average) of the distinct message IDs sent while the ignition was on, were also sent when ECUs were awakened while the ignition was off. Such a high number/portion of ECUs being awakened from the wake-up message and thus sending more message IDs on the bus is because they had numerous standby functions installed for enhanced driver’s experience and convenience (e.g., PKES/RKE, hands-free trunk opening, anti-theft)—a
Figure 8: Setup for measuring battery drain/consumption. The discharge current from our test vehicle’s battery was measured using a multi-meter.

5.2 Battery-Drain Attack

After verifying that the ECUs in our test vehicles can be awakened via basically any wake-up message (even with all 1s in ID, DLC, and DATA fields), we mounted 4 different types of battery-drain attack on one of our test vehicles: 1) simple wake-up, 2) power mode control, 3) repetitive door unlock & lock, and 4) opening the trunk. We were able to reverse-engineer the control messages for those functionalities via the proposed driver-context-based reverse-engineering.

In order to measure the drained/discharged current from the car battery, we disconnected the negative cable from the negative battery terminal and connected our multimeter in series to the battery, i.e., one probe to the negative cable and the other to the battery terminal. We conducted the battery current draw test from the negative side to prevent accidental shorting and while the vehicle was parked with its ignition off. Then, as shown in Fig. 8, we injected (iterative) sequence of control messages to the vehicle through the OBD-II port.

**Drained current.** Table 2 summarizes how much current (on average) was measured to be drawn from the vehicle battery when each attack was mounted additionally. When the ignition was off and all ECUs were either asleep or completely off, i.e., when we did not wake up any ECU, the consumed current was 12.2mA. As expected, this value was below the parasitic drain threshold, which is about 30mA. However, when we just woke up the ECUs, the discharged current exceeded that threshold and drained 42mA. Exceeding the parasitic drain threshold even slightly is considered to
be a serious/critical problem. As we controlled more functions that indirectly illuminated exterior/interior lights, the average battery consumption increased further to 74.5, 101.1, and 153.3 mA.

More worse cases. It is important to note that, depending on the vehicle model, there could/would be (much) more of such controllable functions, thus allowing the attacker to drain the battery more quickly and easily. However, we only show 4 controls as examples for the proposed battery-drain attack since they are already very critical. Moreover, if the attacks are launched at night time when the exterior brightness is low, the car headlights will always come on (as one type of a welcome light) when the car is unlocked. As a result, the current drain will further increase sharply, i.e., drain the battery very quickly. However, in order to show the minimum drain/discharge, i.e., the worst possible case for the adversary, we conducted all our experiments outdoor during day time.

Expected battery operation time. In order to better understand how the increased battery current consumption relates to how quickly the attacker can immobilize the car, we determine the battery operation time as follows. Consider a 45 Ah battery, which is the standard car battery capacity, with a State-of-Charge (SoC) of 70%—the average battery SoC of a passenger vehicle—when parked. Then, since the minimum SoC for a cold start is considered to be 50% in the worst case [12], i.e., worst-case for the adversary, our test vehicle’s battery can theoretically remain idle/parked for up to \( \frac{45 \text{ Ah} \times (0.7 - 0.5)}{12.2 \text{ mAh}} \approx 737.7 \text{ hours} \approx 30.7 \text{ days} \); something that is normally expected. Note that this is the theoretically maximum battery operation time since we considered the worst possible case for its derivation.

One can see from Table 2 how the maximum battery operation time was reduced as different types of battery-drain attacks were mounted. Theoretically, with the 4 control functions, it only takes a maximum of 2.44 days for an adversary to immobilize the vehicle via a battery-drain attack, i.e., can be achieved over the weekends. It is important to note, however, that it could take much shorter especially when the temperature is low and the battery is aged. More interestingly, in reality, the actual battery operation time is known to be much shorter than the theoretical/ideal value, i.e., much shorter than the times shown in Table 2. According to the Peukert’s Law, because of intrinsic losses and the Coulombic efficiency being always less than 100%, the actual battery operation time is much lower than the ideal/theoretic value in which the latter assumes the battery to be ideal [26]. In fact, since the intrinsic losses in the battery escalate as load increases, the battery capacity is known to drop sharply as the drained/discharged current increases. This implies that as the adversary controls more functionalities, s/he can not only increase the battery consumption but also decrease the available battery capacity at the same time! So, s/he can significantly reduce the battery operation time via a battery-drain attack, thus crippling the vehicle quickly, perhaps overnight.

5.3 Denial-of-Body-control (DoB) Attack

Through experiments on one of our test vehicles, we also verified the consequences of the proposed DoB attack. Using the connected OBD-II device, we mounted a DoB attack as described in Section 4.4.
Figure 9: Consequence of a DoB attack. After the attack, the vehicle could no longer detect that the key fob was inside it.

After launching the DoB attack on one of our parked test vehicles, taking only a few seconds, we confirmed from the CAN traffic that all ECUs on the bus were continuously incurring and/or experiencing errors, causing all the ECUs to enter the bus-off state. After mounting the DoB attack, we observed most, but not all of the ECUs recovered from the bus-off state as configured. We observed that the number of distinct message IDs sent on the bus was actually reduced by 6 after the DoB attack. By mapping those missing IDs to the actual transmitter ECU using the DBC file, we found that the RCM (Remote Control Module) did not recover from the bus-off, i.e., remained shut down, most probably due to its distinct recovery policy configuration (perhaps for anti-theft/engine-immobilizer purposes). Since the RCM was indefinitely off, the key fob was not authenticated and thus could not establish a connection to the vehicle. As shown in Fig. 9, the vehicle could not detect that the key was in its vicinity; the key was in fact placed right in front of the dashboard. This consequence of the proposed DoB attack was reproducible on our test vehicle.

Of course, remote key fobs are now equipped with RFID chips that can be used for authentication, connection establishment, and thus starting the vehicle in case of a dead key fob battery. However, since the communication between the key fob’s RFID and the vehicle was also configured to be governed by the RCM, the RFID-based (emergency) start did not work either. More interestingly, after mounting the DoB attack, when we tried to open the doors or trunk to enter the car, we could not since the RCM was not functioning and thus failed to authenticate the key fob. The only way to get in was actually using the back-up physical key hidden in the key fob. Note, however, that the car did not start anyway (as shown in Fig. 9) even though we were able to enter it!

As discussed earlier, this consequence comes from the fact that OEMs (or their ECUs) may have different bus-off recovery configurations. In our test vehicle, the setting of an RCM to not recover from the bus-off “favors” the attacker in mounting a critical DoB attack. We found the only way to restore the vehicle back to its original state after a DoB attack was to disconnect the battery, wait for a few minutes, and re-
connect the battery. Such a process resets the states stored in each ECU and thus lets them run in their original/intended states. However, imagining a victim confronting the symptoms of DoB attack, i.e., the key fob neither working nor being detected, s/he might first try to change the key fob battery. Obviously, since that won’t work, s/he would consider the car battery completely dead and therefore, would probably have the car towed to the service station for a battery replacement, wasting money and time unnecessarily!

6 Related Work

Exploiting a remotely compromised ECUs, researchers have shown how various vehicle maneuvers (e.g., braking, steering) can be (maliciously) controlled by injecting packets into the in-vehicle network [7, 8]. Similarly, in 2015, researchers were able to compromise and remotely kill a Jeep Cherokee running on a highway [5], which triggered a recall of 1.4 million vehicles. In 2016 and 2017, researchers were able to hack a Tesla model S and model X, respectively, exploiting software vulnerabilities, and controlled vehicle maneuvers [6]. Researchers have also demonstrated that an adversary can also shut down a specific ECU or even the entire in-vehicle network merely via packet injection [3]. The authors of [27] also succeeded in a remote attack via a vehicle’s tire pressure monitoring system (TPMS). Researchers also proposed new hardware which can generate/fabricate magnetic fields, spoof the wheel speed sensor on a vehicle, and thus activate the Anti-lock Braking System (ABS) [28].

Although such attacks were effective, they were mounted and thus considered malicious only when the vehicle is running. In contrast, we focused on, and proposed new attacks that are effective when the ignition is off. Moreover, the controlled functionalities had to be very different from existing attacks since those that are considered “critical” are different. The steering being maliciously controlled is clearly safety-critical when the vehicle is running, but not so when the vehicle is parked; illumination of exterior/interior lights might be a more critical problem!

7 Discussion

Countermeasures. As the proposed battery-drain attack and DoB attack are mounted with the ignition off, the design principles of their countermeasures have to be very different from the state-of-the-art defenses, which are mostly concerned with attacks on “running” vehicles. For example, as of the current CAN standard, since the wake-up itself can be achieved with any CAN message having a 010 bit-sequence, adding MAC or message encryption cannot prevent the adversary from waking up ECUs; a message with MAC/encryption will still have such a sequence.

The cornerstone of battery-drain attack and DoB attack is to wake up ECUs asleep on the bus while the ignition is off. So, as their feasible and effective countermeasure, one can think of continuously running an Intrusion Detection System (IDS) even when the ignition is off in order to capture any abnormal wake-up messages; wake-up messages usually should not be seen very frequently. However, since the operation of an
IDS would increase the current drawn from the battery, such an approach may defeat the very purpose of reducing battery consumption. Like other ECUs asleep, the IDS ECU can also be configured to sleep most of the time and wake up only when it sees a wake-up message. In such a case, as a countermeasure against both types of attack, the wake-up pattern of an IDS can be modeled and used to detect any abnormal wake-up requests on the bus without continuously running it. Similarly, the IDS can be configured to wake up periodically, check the battery SoC—if there was any significant drain recently—and react accordingly. Moreover, especially for the DoB attack, how to recover from the bus-off state has to be re-examined in order to prevent the consequences of the DoB attack, as we had demonstrated.

**Enhanced wake-up functionality.** Partial networking—i.e., partial deactivation of subnets within a given network—has been discussed and planned to be installed by car manufacturers. This is to reduce energy consumption and thus CO$_2$ emissions [13]. In such a setting, only the pre-defined wake-up messages that pass the wake-up masks/filters of selective ECUs can wake up those ECUs during operation. However, since that message is “pre-defined” and can easily be learned by observing the CAN traffic and its sudden change in the number of message IDs (as in Section 4.3.3), the wake-up message itself can still be learned and used by an adversary. In fact, the introduction of partial networking will increase the number of ECUs to sleep rather than being completely turned off, and thus provide a larger attack space for mounting the proposed attacks.

**Limitations.** We considered/assumed that the (CAN) adversary has access to the in-vehicle network via a compromised ECU (either a compromised OBD-II dongle or an in-vehicle ECU)—a limitation of our approach—to mount the proposed attacks. However, we must not overlook the fact that the adversary might not even need a compromised ECU to mount the proposed attacks. To further enhance the driver’s convenience, companies such as Volvo [29], Lexus [30], and Tesla [31] started to let car owners unlock/lock their cars by using their smartphone apps with an eventual goal to totally replace key fobs with smartphone software. This means the existence of another (new) attack vector for mounting battery-drain attack: compromising those apps! As more of such vehicle-related technologies evolve and get deployed, there may be more (intelligent) ways of mounting the proposed attacks.

Although we succeeded in mounting battery-drain attack and DoB attack on our 2017 model-year test vehicle, not many ECUs were awakened when a wake-up message was injected in older vehicles, because they had less standby functions than newer models, and thus had less ECUs asleep while the ignition was off. The proposed attacks will likely be easier and more effective to be mounted on newer models as we observed in waking up more ECUs in newer vehicles (Fig. 7). For the DoB attack, however, since its success/feasibility will totally depend on how the OEMs configured their “bus-off recovery” for different ECUs, it might not be as feasible as battery-drain attack. The battery-drain attack will still be feasible unless the standard wake-up procedure is changed or standby functions are not installed.
8 Conclusion

In this paper, we discovered two new important vulnerabilities in vehicle availability: battery-drain and Denial-of-Body-control (DoB) attacks. They are counter-intuitive in that attacks are commonly believed to be possible and effective only while the ignition is on. Specifically, we have shown that an attacker can wake up ECUs on the bus, even while the ignition is off, mount the proposed attacks, and then immobilize a parked vehicle with its ignition off. Through extensive experiments on real vehicles, we showed that such attacks are indeed easy to mount and very critical to vehicle availability. Ironically, the adversary exploits, as attack vectors, the in-vehicle network features originally designed for either energy-efficiency (e.g., simple wake-up signals) or enhanced user/driver experience/convenience (e.g., standby functions). There could still remain different types of unknown and unintuitive vehicle vulnerabilities, like the two proposed here. It is therefore important to analyze and understand what consequences existing built-in/standardized functionalities can lead to. This calls for concerted efforts from both academia and industry on this possibility and countermeasures thereof in order to build secure vehicles.

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26
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