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Current Implementations of Over-the-Air Updates

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EXECUTIVE SUMMARY

Over-the-air (OTA) updates have become a significant aspect of the future development of connected vehicles. OEMs can address safety and security concerns, as well as provide a better customer experience, by delivering software improvements to vehicles faster and without requiring a visit to a service center.

OTA updates will enable OEMs to address security, safety, and performance concerns much faster, at a lower cost, and allow delivery of updates in a manner more convenient to vehicle owners. From a cybersecurity perspective, this is important, as the number of security vulnerabilities in vehicles continues to grow (Sibros, 2022). Additionally, recalls are increasingly being addressed by software updates, potentially resolving recall issues faster. From March 2022–March 2023, 8.5 million vehicle units were recalled due to software-based or electrical components (Sibros, 2022; *Vehicle Recalls*, 2023). Advanced driver assistance systems and automated driving systems are continually being developed and improved. OTA updates are an enabling technology that allows improvements to these technologies to be realized on vehicles at a much more rapid pace than in the past.

The objective of this report is to understand the capabilities, challenges, and characteristics of implementations of OTA updates in vehicles. This report summarizes and details key findings of OTA updates in current vehicles and focuses on the potential challenges in adopting this new advancement in technology.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

ECU	electronic control unit
NHTSA	National Highway Traffic Safety Administration
OTA	over-the-air

CHAPTER 1. INTRODUCTION

Today's vehicles are equipped with highly sophisticated computational abilities that control many performance and functional aspects of the vehicle. Modern vehicles can contain between 100–150 electronic control units (ECUs) connected in a complex network, and running up to 100 million lines of code (Pike, 2022; Sibros, 2022). That is more than four times the amount of code in a fighter jet and more code than in all of Windows 10 (Moore et al., 2022). This amount of code calls for regular updates to correct bugs, address security issues, and ensure that performance criteria are being met. While not all modules, dependencies, and associated code may need updating to fix or improve functionality, some likely will. A structured process for review and testing of these updates can help ensure the software supports safe, secure, and functional operation of the vehicle.

Traditionally, updates have been issued in a transactional relationship between the vehicle owner and manufacturer. Each time an update is released, the vehicle owner must drive to the dealership or a service station for the car to be updated by a service technician. Recent advances now enable updates to be performed wirelessly—i.e., over-the-air (OTA)—eliminating the need for customers to make in-person update visits.

As an example of an update applied in the traditional manner, consider the following case. In April 2022, Toyota announced a recall of up to 458,110 vehicles due to a logic issue in the skid control ECU, which prevented the vehicle stability control system from activating (Koopman, 2022). This problem was addressed by a software update which was performed at the dealer.

Now consider a contrasting OTA update example. In February 2022, Tesla announced a recall to address a heat pump issue that resulted in defrosting problems affecting the front windshield. Unlike the Toyota recall, the Tesla recall was addressed via an OTA update, which resulted in the update being available to customers more quickly and more conveniently.

MARKET ANALYSIS

In addition to the increased complexity and amount of software in modern vehicles, other factors that lead to growing interest in OTA updates include increased demand for electric vehicles, the rise in adoption of connected vehicles, and the ability to address safety recalls more quickly. For OEMs, the primary benefit of comprehensive implementation of OTA updates lies in the potential cost savings associated with future recalls. Vehicle owners desire to have the ability to update their vehicles OTA. According to a survey conducted by IHS Markit, 67% of global consumers who plan to purchase a vehicle expressed a desire for OTA updates in their next vehicle (IHS Markit, 2020).

OTA updates can be used to correct bugs and fix security-related issues within a system, but they can also improve or enable certain vehicle features. In a press conference in 2021, Volvo announced, upon its first OTA update, "A new car is no longer at its finest when it leaves the factory…. It keeps improving over time as additional OTA updates are launched" (Overland, 2021). Automakers have begun to experiment with a shift towards a revenue stream model that unlocks certain features, delivered OTA, based on a subscription or one-time purchase (De Chant, 2021; Lambert, 2020).

SECURITY CONCERNS

Unlike other devices that deliver updates OTA, such as smartphones, the consequences of updating vehicles with malicious or faulty code could lead to events that are devastating to human life (Mahmood et al., 2022). Software packages are continuously being developed and distributed to vehicles, which offers an attractive attack vector for malicious actors. The National Highway Traffic Safety Administration (NHTSA) published a draft update to the agency's 2016 Best Practices, titled *Cybersecurity Best Practices for the Safety of Modern Vehicles* in September 2022. These best practices outline cyber-related hygiene procedures that OEMs should take into consideration. The report suggests that, when designing security measures, risks associated with the OTA update infrastructure should be considered. These infrastructure updates include compromised servers, insider threats, man-in-the-middle attacks, and protocol vulnerabilities (NHTSA, 2022). As detailed in Figure 1, an outside attack via backdoor access to the OEM cloud has the potential of utilizing the OTA update system as a form of mass distribution to a fleet of vehicles (Bar, 2019).

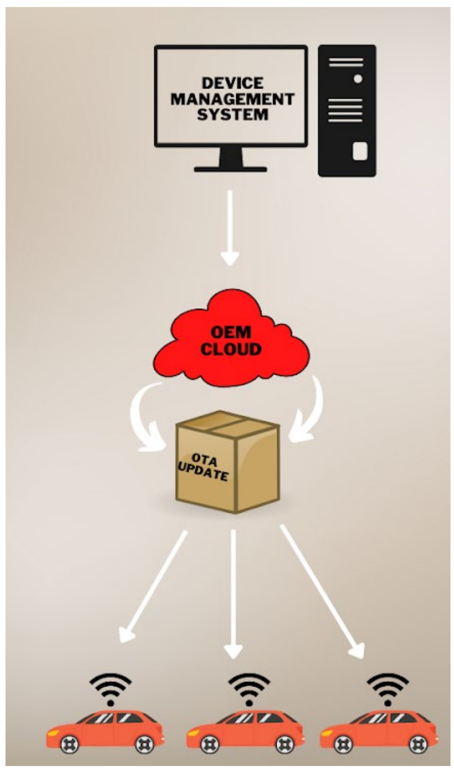

Figure 1. Diagram. OEM cloud exploitation.

SECURITY BENEFITS OF OTA

Aside from securing the OTA update infrastructure, delivering security updates to affected devices quickly has proven to be important in limiting the negative impacts of vulnerable software. Application updates via app stores and automatic updates (e.g., Windows Updates) have been effective at getting updates to devices and thereby reducing the number of vulnerable devices that attackers can compromise. The ability to deliver updates to devices quickly is one of the primary security benefits that OTA updates offer.

In devices such as laptops and smartphones, end users have been performing OTA updates for years. However, most consumers are not familiar with updating their vehicles in the same manner, and it seems reasonable that vehicle updates are perceived differently from smartphone updates. In order for consumers to be comfortable taking advantage of the security benefits of OTA updates in vehicles, they will need trust in the process. Faulty updates, such as a Rivian update that caused the infotainment center in some vehicles to stop working after an update,[1] are likely to cause consumers to doubt the update process. In the case of smartphone applications, negative experiences with updates does impact the level of comfort users have with future updates (Mathur & Chetty, 2017). We are unaware of any research that studies the magnitude of the impact these update problems are expected to have on adoption of OTA updates in vehicles.

SAFETY CONCERNS

In addition to traditional cybersecurity concerns that updates can address, there are also safety concerns that can be addressed by updating the software on a vehicle. This could be in the form of addressing a safety defect (i.e., a recall) or an update that improves the performance of a safety-related feature. In the past, a visit to a dealer or service station would be required, where a trained technician would apply the update following a structured procedure to ensure the process was successful. Performing this update OTA has the potential to significantly decrease the time it takes to get the update on vehicles. However, an OTA update will no longer have a trained technician involved and would therefore require the software update process itself to ensure a successful installation.

Not only does the update process itself need to be reliable, but the software development, testing, and verification process prior to the update being made available must be rigorous. This process does involve ensuring the installation process will be successful but perhaps more importantly that the update itself will result in a vehicle that operates as well or better than before the update was applied. In vehicles, this is especially challenging due to the variety of conditions in which vehicles operate and the different configurations of the hardware and components in vehicles.

[1] https://electrek.co/2023/11/14/rivian-software-update-bricks-infotainment-system-fix-not-obvious/

CHAPTER 2. SAMPLE IMPLEMENTATIONS

Automakers have different implementation strategies for delivering OTA updates to vehicles (Halder et al., 2020). Likewise, governments and regulatory bodies are taking a variety of approaches to regulating OTA updates. For instance, the World Forum for Harmonization for Vehicle Regulations (WP.29) has developed Regulation No. 156 (R156) describing what will be required for vehicle-related software updates and software update management systems. In order to sell vehicles in WP.29 member countries, OEMs must ensure that these requirements are met. Failing to do so could lead to financial losses stemming from delays in vehicle authorization, trade limitations, and legal obligations (Sikaria, 2021). Requirements of R156 relating to Software Update Management Systems include the following: information security best practices, version comparison, target identification processes, and safety assurance mechanisms. As previously noted, in 2022, NHTSA released an update to *Cybersecurity Best Practices for Safety of Modern Vehicles*, which contains a section devoted specifically to OTA updates . Finally, ISO 24089: *Road Vehicles, Software Update Engineering* was released in February 2023 and provides guidance on the steps that should be taken to ensure that updates are developed, tested, delivered, and applied to vehicles in a safe and secure manner. This has provided the industry with many sources of guidance that still leave many implementation decisions for OEMs to make. Below is a sampling of our observation of six current implementations of OTA updates in production vehicles.

2022 FORD F-150

Ford uses SYNC 4 as the 2022 F-150's operating system. OTA updates are released on a rolling basis and are set to update automatically by default (Ford, 2023c). When an update is released, users are notified through the Ford Pass mobile app as well as the infotainment system. As part of the notification process, Ford publishes additional information about what is included in the update. The vehicle owner is notified of two types of updates: updates that require owner permission and require that the car be parked with the ignition off (in addition to the other parameters listed below; non-drivable updates) and those that do not require permission and can take place while the car is being driven (drivable updates). Updates that do not require permission will be completed without the owner's involvement, and owners are informed when updates are complete. Non-drivable updates require owner permission prior to installation; the owner will be asked to schedule a time when the vehicle can meet the following requirements, as outlined in Ford's software update specifications (Ford, 2023c, 2023b):

1. Your vehicle is stopped and parked.
2. Your parking brake is set.
3. The update is scheduled for before or after 12 a.m. (not exactly 12 a.m.).
4. Your vehicle's ignition is off.
5. All your doors are closed.
6. Your headlights are turned off.
7. Your vehicle was driven for a minimum of 30 minutes prior to avoid low battery.

If the above criteria are not met, owners will receive a "Vehicle Not Updated" message on the infotainment system, prompting a new scheduled time to reinstall the update, as shown in Figure 2.

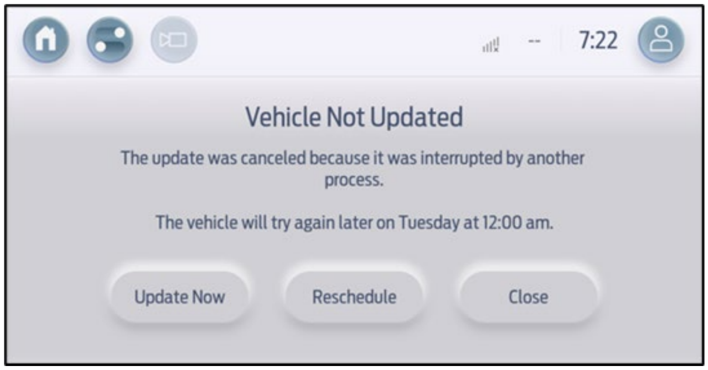

Figure 2. Screen capture. Vehicle not updated notification (Ford, 2023c).

Ford has released an average of 2–7 updates per month. An option to automatically apply updates can be turned off by the vehicle's owner. This option is displayed in the settings of the vehicle's infotainment system; however, Ford recommends keeping automatic updates enabled to ensure the vehicle remains up-to-date. If automatic updates are disabled, the owner must have vehicle notifications turned on in the mobile app to receive information about the update. Ford vehicles connect via private Wi-Fi connection or a premium cellular connection through AT&T (AT&T, 2023; Ford, 2019).

The most common cause of update failures is due to issues related to the Wi-Fi or cellular connection (Ford, 2023a). It is anticipated that vehicles will continue to be able to receive updates at dealerships. This can address the situations where owners encounter update issues, are uncomfortable with OTA updates, or need an update that is not eligible to be delivered OTA.

2022 BMW X5

BMW began using OTA updates to vehicles in 2018. With the introduction of BMW Operating System 7, BMW has been investing resources into the development of what is known as BMW remote software upgrades (Barnwell, 2020). Upon release of an update, users are notified of the option to download the contents of the software update through the My BMW mobile app as well as through the in-vehicle infotainment system. BMW updates can be downloaded to the vehicle's system via the mobile app as a part of the preinstallation process (BMW, 2019). After downloading an update, the vehicle must be parked and remain stationary for 20 minutes for the installation process to take place (BMW, 2023a). At this time, updates are all non-drivable, and the following are additional requirements a vehicle owner must fulfill for the installation to begin (BMW, 2019):

1. Vehicle key kept inside the vehicle.
2. Selector lever in Park.
3. Parking brake applied.

4. No device connected to ODB socket.
5. All exterior lighting is off.

After an update has been initiated, the vehicle owner can lock and leave the vehicle unattended. If the above criteria are not met, vehicle owners will receive a notification that the remote software upgrade has failed, as shown below in Figure 3. When an error occurs during the installation process of the update, measures for system recovery are automatically started. If such measures are unsuccessful, the vehicle will enter a “fail safe” mode where the vehicle is not able to operate, and the engine is turned off. Accordingly, BMW suggests that the vehicle be parked away from public road traffic before the installation process begins (BMW, 2023b).

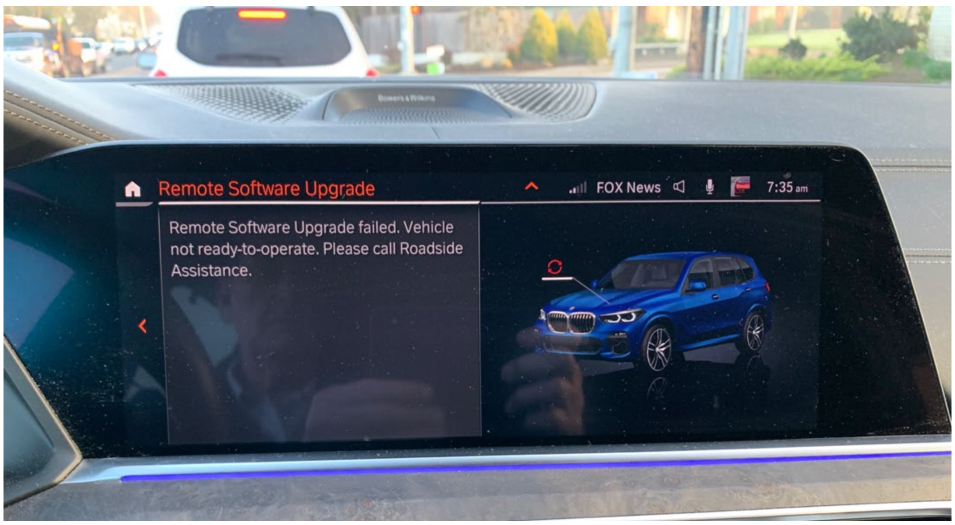

Figure 3. Photo. Update failure after checking for vehicle update.[2]

BMW releases updates every 3 months on average. The BMW X5 offers the option for updates to download to the vehicle automatically through a feature that can be toggled on or off in the My BMW app. The BMW X5 currently offers two methods of connectivity: through a secure Wi-Fi connection, or via a premium T-Mobile plan (T-Mobile, 2023).

2022 SUBARU OUTBACK XT

Subaru utilizes the Starlink operating system installed in the Outback XT to perform OTA updates. Updates are released as needed throughout the year; Subaru currently provides updates to the navigation and infotainment subsystems. Upon release of an update, vehicle owners will receive an email notification from Subaru, a notification through the infotainment system, and/or a notification through the My Subaru mobile app (Hutton, Rick, 2020).

Once an update becomes available, the vehicle may connect through a Wi-Fi network or a mobile hotspot. The download and installation process are initiated from the infotainment

[2] https://g05.bimmerpost.com/forums/showthread.php?t=1698654

system. For optimal performance, Subaru suggests the following conditions be met before the update is initiated (Hutton, Rick, 2020):

1. Move the vehicle to an outside location where the engine can be safely started and kept idling during the update process.
2. Never idle the vehicle in a closed space such as a garage, even if the garage door is open.
3. Once the vehicle is in a safe location, be sure the vehicle is in Park and the parking brake is fully engaged.
4. Unplug any devices, cables, or other USB drives from the vehicle's USB ports.

Once the update has been properly downloaded to the vehicle, the infotainment system prompts the user to continue with the installation process as shown in Figure 4, left. Subaru vehicle owners have the option of enabling automatic updates upon release or disabling the function to only allow updates to be downloaded after the owner grants approval for installation. The default settings for the vehicle include the vehicle automatically checking for updates toggled on and automatically downloading updates toggled off.

The most common reason for an update to fail is due to internet connectivity issues. Should this occur, an error message prompts the user to connect to an internet source, as shown in Figure 4, right. Subaru vehicles can connect through Wi-Fi, a mobile hotspot, or through a premium plan purchased through AT&T (Subaru, 2023).

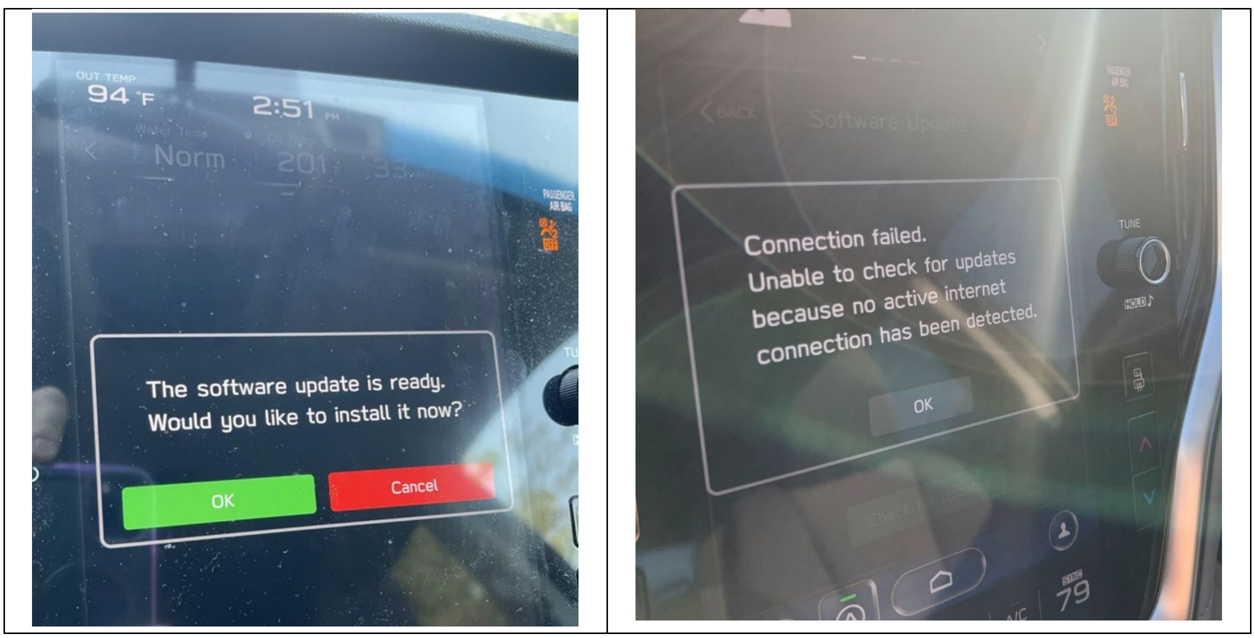

Figure 4. Photos. Left: Subaru OTA update available.[3] Right: connection failure.

[3] https://www.reddit.com/r/Subaru_Outback/comments/xkf2w3/ota_update/

2022 RIVIAN R1S

Rivian uses a combination of proprietary software and third-party components to deliver OTA updates to the R1S (Rivian, 2023b). Upon the release of an update, customers are alerted through the Rivian mobile app notification as well as through the Rivian infotainment system (Rivian, 2023c). Information related to current versions of software and a history of updates is available in the infotainment system or via the Rivian mobile app (Rivian, 2023b). As Rivian relies almost exclusively on their OTA updates, the following conditions must be satisfied before the installation of OTA updates to ensure update success (Rivian, 2023e):

1. The vehicle must be parked.
2. Available charge range distance must be above 35 miles.
3. Vehicle must not be fast charging.

Rivian releases OTA updates 1–2 times per month on average, which by default are set to update automatically (Rivian, 2023d). Figure 5 shows the message presented when an OTA update is available from Rivian; the message includes an estimated time to complete the installation.

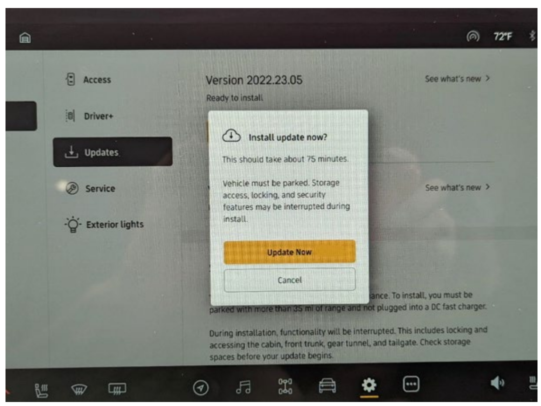

Figure 5. Photo. Rivian software update.[4]

Reported OTA update failures have been primarily due to connectivity issues. An additional problem that has caused Rivian OTA updates to fail is related to issues with an internal 12-volt battery.[5] This battery is responsible for powering the vehicle during an update and will cause an update failure if power is disconnected. Rivian does not have a traditional vehicle network and does not require vehicle owners to return to a dealership for update problems (Loveday, 2022). Rivian vehicles are connected wirelessly through either a 4G LTE or Wi-Fi connection (Rivian, 2023a).

2022 VOLVO XC60

Volvo released OTA capabilities for the XC60 in 2022. Cars with the ability to update OTA are given the opportunity to download updates while driving or if the vehicle is in “active mode,” meaning that the car’s infotainment system is turned on (Volvo, 2023b). Once downloaded, the

[4] https://www.reddit.com/r/Rivian/comments/vtwzuh/software_update_is_here/
[5] https://s00n.rivianstories.com/posts/my-ota-failed-and-rivian-mobile-service-saved-the-day

vehicle owner is alerted through an infotainment system notification as well as the mobile Volvo app that the package is ready for installation. The vehicle owner can schedule the date and time for the installation through the vehicle infotainment system. The following are requirements listed by Volvo before installation of an OTA update can begin (Volvo, 2023b).

1. The car needs to be locked during software installation. The vehicle cannot be used while the installation is in progress.
2. For pure electric vehicles, the high-voltage battery level must be charged to at least 40% before installation.
    a. It is important that the vehicle's high-voltage battery is not charged during the software installation process.

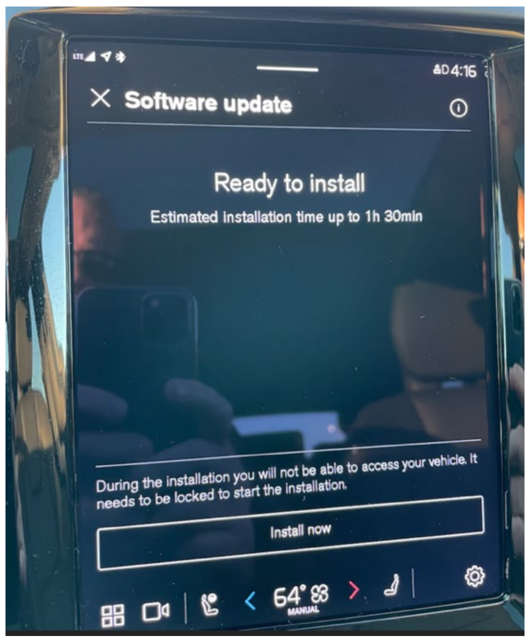

Figure 6. Photo. Volvo update installation.[6]

Figure 6 above shows the information presented when an update is ready for installation. After the installation of an update begins, vehicle owners can exit the vehicle and lock the doors. Once the update has been completed, a notification is then sent to the vehicle's infotainment system, as well as to the vehicle owner's Volvo Cars mobile app (Volvo, 2023b). Should an update fail to install, Volvo recommends contacting a Volvo dealership for guided assistance.

Volvo releases new OTA updates approximately every 6–8 weeks (Volvo, 2023b). Updates are set to download automatically by default; however, users also have the option to turn this feature off and selectively download available updates.

For this vehicle, Volvo offers two methods of connectivity. The first is a connection via Wi-Fi, and the second is through a premium AT&T cellular plan (Volvo, 2023a). Most updates are

[6] https://www.swedespeed.com/threads/how-to-force-ota-update-on-22-xc60-ymmv.649514/

available remotely; however, some early access to features requires the vehicle to return to a dealership to receive access. For example, the V2.4 update released solutions to a false "Service Required" message related to Parking Assistance as well as Drivetrain optimization adjustments. The contents of this update were not available remotely until the release of V2.5, which did not take place until months later.[7] Information related to OTA update version tracking and release notes are found on the Volvo website and through the vehicle's infotainment system settings (Volvo, 2023b).

2022 CHEVROLET BOLT EUV

The last vehicle sampled is the 2022 Chevrolet Bolt. OTA update technology was first introduced to the Bolt in April 2018 (Loveday, 2019). Software updates released OTA thus far are only relevant to updating the infotainment system. This includes, but is not limited to, maps, interface, applications, and bug fixes. Each vehicle is equipped with "OnStar," an infotainment software that provides connectivity to vehicles. By default, the Bolt has automatic downloads of updates disabled and users are prompted to download updates. The Update Available prompt from an older model Bolt is show in in Figure 7 below. Vehicle owners can also manually check for updates through the system settings. The Bolt can be used normally or can be charging during the update download process. In order to install an update, the following conditions must be met:

1. The vehicle must be shifted into P (Park) in a safe and secure location.
2. Ignition in the OFF position.
3. Vehicle not connected to a charging station.

Figure 7. Photo. Older model Chevrolet Bolt update available (Loveday, 2019).

The infotainment system will notify the owner of update success or display error messages after the installation process has completed. Software update installation is expected to be complete in 20 minutes or less (Chevrolet, 2023). The most common issue to occur when downloading an update is loss of network connectivity. Additional issues concerning update failure can include vehicle conditions such as the battery level falling too low or the outside temperature being too low (Loveday, 2019). To date, no updates have been released for the 2022 Bolt EUV. Connectivity for downloading updates is available via the vehicle's built in 4G LTE with

[7] https://forums.whirlpool.net.au/archive/3jm6pzrn

premium plans. In addition, the vehicle can connect through a Wi-Fi or secured mobile device hotspot connection.

CHAPTER 3. CONCLUSION AND FUTURE OPPORTUNITIES

Table 1 represents a condensed version of the OTA update capabilities for each sampled vehicle discussed in the previous section.

Table 1. OTA update capabilities – condensed.

Automobile company Model Year	Ford F-150 2022	BMW X5 2022	Subaru Outback 2022	Rivian R1S 2022	VOLVO XC60 2022	Chevy Bolt 2022
Do vehicles support OTA updates?	Yes	Yes	Yes	Yes	Yes	Yes
Are some updates required to return to the dealership?	No	Yes	Yes	No	No	Yes
Can updates be downloaded while driving?	Yes	No	No	No	No	Yes
Do update installation require vehicle to be parked?	Yes	Yes	Yes	Yes	Yes	Yes
How does the vehicle connect to the Internet?	Wi-Fi and Cellular	Wi-Fi and Cellular	Wi-Fi	Wi-Fi & Cellular	Wi-Fi & Cellular	Wi-Fi & Cellular
Are Firmware OTA updates supported?	No	No	No	Yes	No	No
Are Software OTA updates supported?	Yes	Yes	Yes	Yes	Yes	Yes
How often are updates sent out?	2–7 per month	Quarterly	As Needed	1–2 per month	"Few times a year"	As Needed
How does the owner know about the update?	App/System	App/System	System	App/System	App/System	App/System
How does the owner Track updates?	Mobile App	Mobile App	Infotainment	Website	Infotainment/Website	Infotainment
Can the owner disable automatic updates?	Yes	Yes	Yes	No	Yes	No
How long can you ignore updates?	Indefinitely	Indefinitely	Indefinitely	Indefinitely	Indefinitely	Indefinitely
What happens if an update fails?	Notification	Fail/safe mode	Notification	Notification	Notification	Unknown
What support is available for update failure?	Service Dealership	Service Dealership	Service Dealership	Mobile Service	Service Dealership	Service Dealership

From the descriptions of the types of OTA updates available in the vehicles provided in the preceding sections and the results summarized in Table 1, we can see that many aspects of OTA updates are the same or similar across vehicles. This is helpful to know as OTA updates become more mature and owners become increasingly aware of their existence.

The most notable difference observed in Table 1 is the variability in how often updates are made available OTA. This is an area for future research, as the reason for this variability could be far reaching and range from company culture to code quality. Another explanation to explore is the types of vehicle systems being updated OTA (e.g., safety critical versus an infotainment system). There might also be guidance needed from regulatory bodies or industry to help companies balance update frequency and velocity with ensuring that the testing and validation process is sufficient.

We also noted differences in the way owners interact with OTA updates and the information available about the updates. For instance, each model analyzed allowed interaction with updates via the infotainment system. However, the information about the updates was different for each vehicle. Presumably, the system(s) being updated would also influence the type of information being presented (i.e., a map update versus an update to an ECU responsible for a safety-critical system). An opportunity for future research is to develop an understanding of what information vehicle owners need and want about updates, as well as their perception and willingness to apply updates. Finally, there is a gap in the literature related to characteristics about how vehicle owners are currently applying updates.

There is an opportunity to differentiate automotive OTA updates from traditional updates (e.g., Windows Updates) by providing more information about the testing that was performed for each update. This could be testing specific to the update or more general information that describes how the manufacturer tests all changes to software in vehicles. Regulatory requirements (e.g., WP.29) require updates to be well tested (Costantino et al., 2022), so this represents an opportunity to meet those requirements while also accelerating the industry towards transparency when it comes to updates pertaining to code running on vehicles.

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