# Automated Cross-Platform Reverse Engineering of CAN Bus Commands From Mobile Apps

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[1]Ohio State University
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NDSS 2020

# In-vehicle Network and CAN Bus

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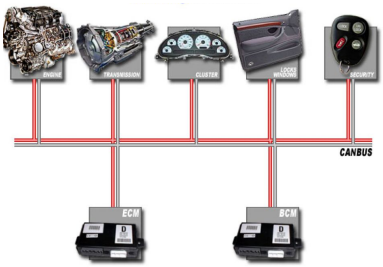
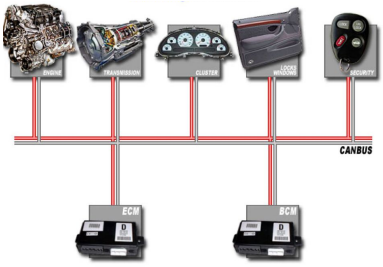



Control Area Network (CAN) bus.

# In-vehicle Network and CAN Bus




Control Area Network (CAN) bus.

| SOF | Identifier | RTR | IDE | DLC | Data Field | | | | | | | | CRC | ACK | EOF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Byte 0 | Byte 1 | Byte 2 | Byte 3 | Byte 4 | Byte 5 | Byte 6 | Byte 7 | | | |

CAN bus command.

# Applications of CAN Bus Commands

Driver Behavior Monitoring

An On Board Diagnostic (OBD-II) dongle, used by insurance company Progressive to monitor driver behavior

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Driver Behavior Monitoring

An On Board Diagnostic (OBD-II) dongle, used by insurance company Progressive to monitor driver behavior

Vehicle Control


An In-Vehicle Infotainment (IVI) system.

# Applications of CAN Bus Commands: recently on **Autonomous Driving**





# Applications of CAN Bus Commands: Security

Vehicle Hacking

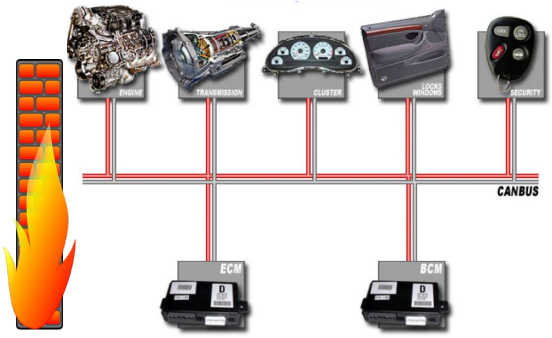
The Jeep Cherokee hacking [MV15].

# Applications of CAN Bus Commands: Security

## Vehicle Hacking

The Jeep Cherokee hacking [MV15].

## Vehicle Security Monitoring




CAN Bus Firewall [HKD11] [MA11].

# Reverse Engineering of CAN Bus Commands

## State-of-the-art

1. Fuzzing with random CAN bus commands [KCR+10] [LCC+15].
2. Manually triggering physical actions and observing the CAN bus [car] [wir].

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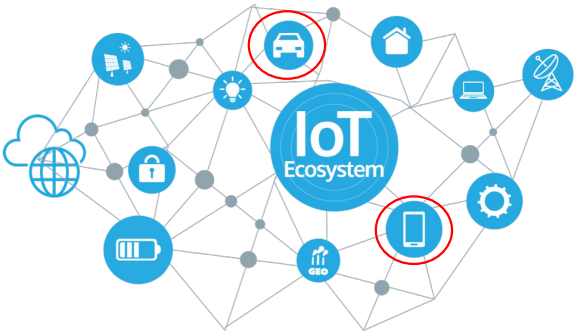
## Shortcoming

1. **Limited scalability**. CAN bus commands are highly *customized* and *diversified*.
2. **Excessive cost**. Significant *manual effort* and real *automobiles* are required.

# Our Observation



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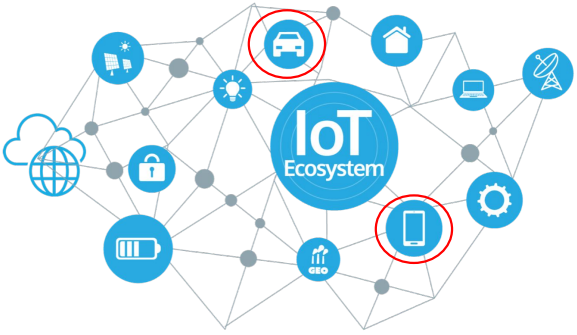



IVI App

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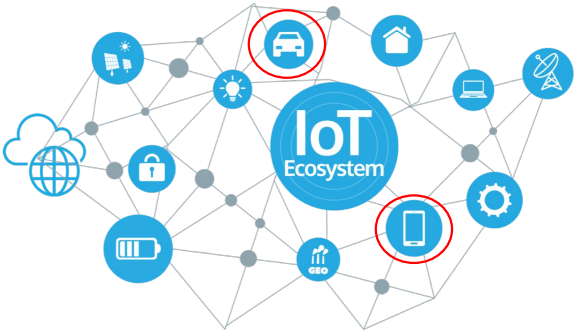



IVI App


OBD-II Dongle App

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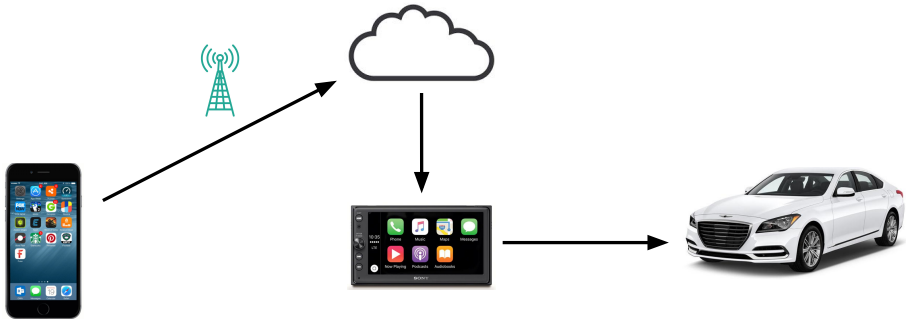

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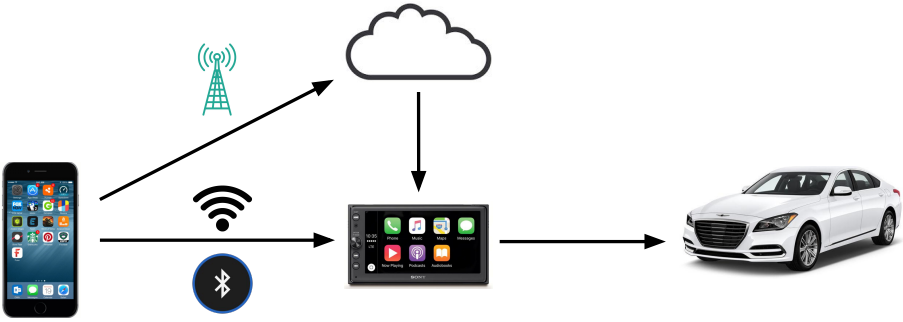

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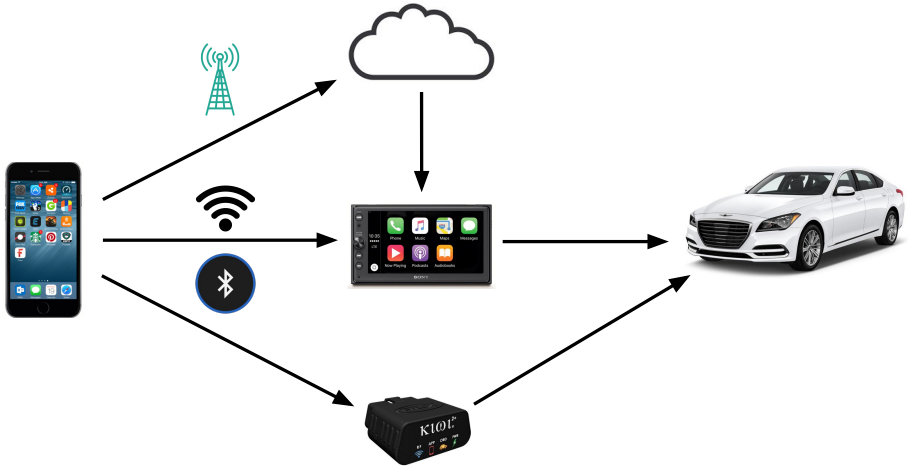

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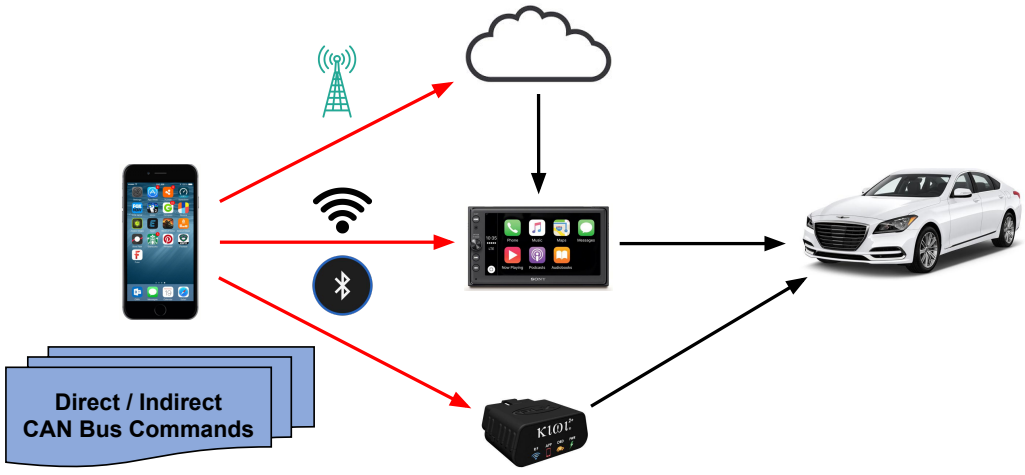

# Our Contributions

1. **Novel Approach**. We propose a cost-effective and automatic approach for reverse engineering CAN bus commands through analyzing mobile apps.
2. **Effective Techniques**. We design a suite of effective techniques to uncover CAN bus command **syntactics** (structure and format) and **semantics** (meaning and functionality).
3. **Implementation and Evaluation**. We implemented CANHUNTER on both Android and iOS platforms, and evaluated it with $236$ car mobile apps. It discovered $182,619$ unique CAN bus commands in which $86.1\%$ of them are recovered with semantics.

# Challenges and Insights

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1. Precisely identify CAN bus command execution path
2. Command syntactics recovery
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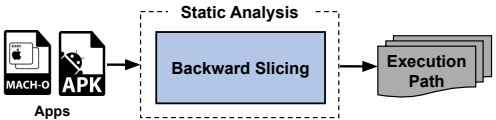
## Solutions

1. Identify execution path with **backward program slicing**
2. Syntactics recovery with **dynamic forced execution**
3. Semantics recovery with **UI correlation** and **function argument association**

# Overview of CANHunter


Apps

# Overview of CANHunter



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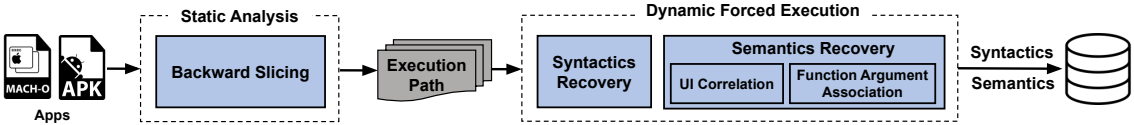

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WorkableModell.createWorkableECUKategorie(a3)
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42  v5.writeValue(v9,v14,1) // Target API
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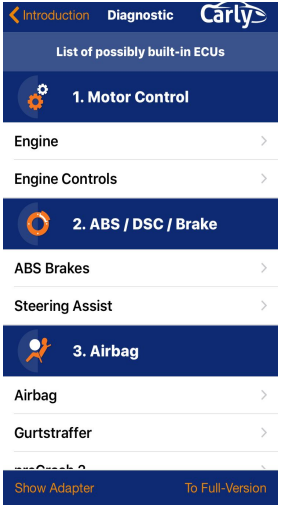

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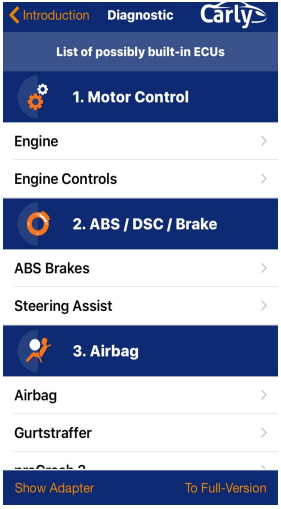

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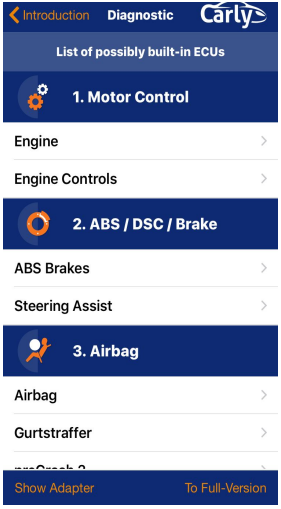

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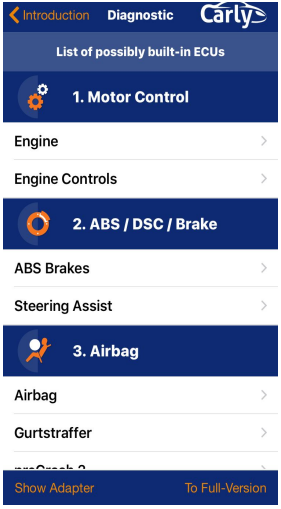

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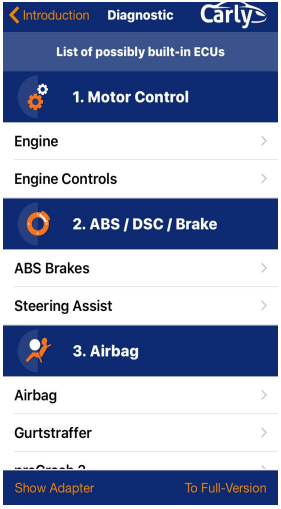

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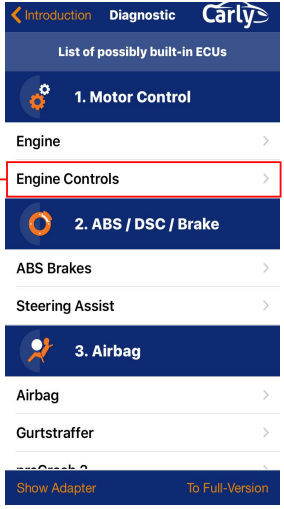

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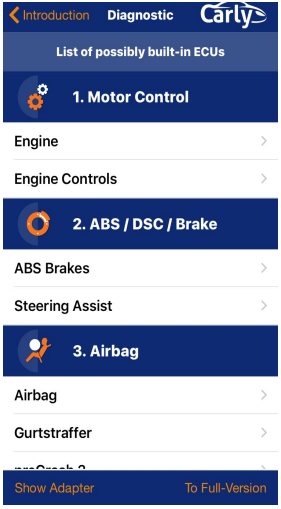

# Result Characteristics by App Categories

| | # Total | # Dongle | # IVI |
|---|---|---|---|
| Android | 122 | 74 | 48 |
| iOS | 114 | 72 | 42 |
| Total (Android ∪ iOS) | 236 | 146 | 90 |
| Overlapped apps (Android ∩ iOS) | 79 | 38 | 41 |

Table: Distribution of collected apps.

1. We crawled 236 vehicle apps in April 2019
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3.
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5. 20 apps are obfuscated

# Result Characteristics by App Categories

## Indirect (i.e., Interpreted) CAN Commands

1. IVI apps usually use *interpreted commands* for vehicle control
2. Interpreted commands are usually strings or numbers

| App | Content | Sent to Cloud | Sent to Vehicle |
|---|---|---|---|
| AcuraLink | HORN_LIGHT, UNLOCK, LOCATION | ✓ | |
| Alpine | frontSpeakerPattern, rearSpeakerPattern | | ✓ |
| Alpine TuneIt | RESUME, PHONE_DIAL_END, AUDIO_FOCUS | ✓ | |
| Audi MMI Connect | LOCK, UNLOCK, G_STAT, FIND_CAR | ✓ | |
| Carbin Control | Climate_Control_Temperature, Control_Fan_Speed | | ✓ |
| Car-Net | Unlock:2, Lock:3, Flash:0, Hornlight:1 | | ✓ |

Table: Interpreted commands from IVI apps.

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Table: Interpreted commands from IVI apps.

# Result Characteristics by Car Models

We identify CAN bus commands from over $360$ car models across $21$ car makers

| Car Maker | # Commands | Car Model |
|---|---|---|
| Audi | 51,517 | A3, A4, A5, A6, A7, A8, Q3, Q5, Q7, S3, S4 |
| Volkswagon | 44,504 | Cabrio, Corrado, Caddy, Gol, Golf, Jetta, |
| Skoda | 11,009 | Citigo, Fabia, Rapid, Superb, Yeti |
| Toyota | 9,030 | Auris, Avensis, Camry, Corolla, Prius, RAV4 |
| BMW | 8,963 | Series 1, 3, 5, M5, X5 |
| Seat | 8,277 | Ibiza, Leon, Altea, Mii, Toledo, Arosa |
| Mercedes | 7,247 | Benz |
| Lexus | 6,087 | CT200, ES350, GS350, GX460, RX450, IS460 |

Table: Distribution of CAN Bus commands over part of car makers.

# Result Characteristics by Semantics

1. $157,296$ $(86.1\%)$ CAN bus commands are recovered with semantics
2. The semantics can be categorized into *diagnosis* and *vehicle control*

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| Semantics | # Commands | Category |
|---|---|---|
| Engine speed | 460 | Diagnosis |
| Coolant temperature | 281 | Diagnosis |
| Throttle angle | 256 | Diagnosis |
| Oil temperature | 176 | Diagnosis |
| Single door lock remote | 60 | Control |
| Blink on unlock key | 42 | Control |
| Sound on remote lock volume | 40 | Control |
| Auto unlock when moving | 27 | Control |

Table: Distribution of CAN bus commands over part of semantics.

# Correctness Evaluation

1. Over 70% of the command syntactics and semantics are validated
2. We tried the following three sources for validation:
   1. Public resource
   2. Cross validation
   3. Real car testing

# Correctness Evaluation

| Car Model | Syntac. | Semantics (Ground Truth) | Semantics (Our Result) | Matched |
|---|---|---|---|---|
| Toyota Prius | 0x727 | Transmission | Transmission | ✓ |
| | 0x7A1 | Steering Assist | Steering Assist | ✓ |
| | 0x7A2 | Park Assist | APGS | ✓ |
| | 0x7E0 | Engine Controls | ECT | ✓ |
| Audi A3 | 0x70C | SteeringWheel | Steering wheel | ✓ |
| | 0x714 | DashBoard | Instrument | ✓ |
| | 0x7E1 | TCMDQ | Transmission | ✓ |
| Seat Ibiza | 0x713 | Brake1ESP | ABS Brakes | ✓ |
| | 0x714 | KombiUDS | Instruments | ✓ |
| Honda Civic | 0x158 | Speed | EAT_TRANS_SPEED | ✓ |
| | 0x17C | Engine RPM | ENG_STATUS | ✓ |
| | 0x1A4 | VSA_STATUS | VSA_WARN_STATUS_ABS | ✓ |
| | 0x324 | Water Tempreature | ENG_TEMP | ✗ |
| | 0x305 | SEATBELT_STATUS | SRS_EDR_DELTA_VMAX | ✗ |
| | 0x35E | CAMERA_MESSAGES | FCM_WARN_STATUS | ✗ |

Table: Part of the commands validated with **public resources**.

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| | 0x7A2 | Park Assist | APGS | ✓ |
| | 0x7E0 | Engine Controls | ECT | ✓ |
| Audi A3 | 0x70C | SteeringWheel | Steering wheel | ✓ |
| | 0x714 | DashBoard | Instrument | ✓ |
| | 0x7E1 | TCMDQ | Transmission | ✓ |
| Seat Ibiza | 0x713 | Brake1ESP | ABS Brakes | ✓ |
| | 0x714 | KombiUDS | Instruments | ✓ |
| Honda Civic | 0x158 | Speed | EAT_TRANS_SPEED | ✓ |
| | 0x17C | Engine RPM | ENG_STATUS | ✓ |
| | 0x1A4 | VSA_STATUS | VSA_WARN_STATUS_ABS | ✓ |
| | 0x324 | Water Tempreature | ENG_TEMP | ✗ |
| | 0x305 | SEATBELT_STATUS | SRS_EDR_DELTA_VMAX | ✗ |
| | 0x35E | CAMERA_MESSAGES | FCM_WARN_STATUS | ✗ |

Table: Part of the commands validated with **public resources**.

# Correctness Evaluation

| App | Android | | iOS | | Overlapped | |
|---|---|---|---|---|---|---|
| | # Syn. | # Sem. | # Syn. | # Sem. | # Syn. | # Sem. |
| BlueDriver | 304 | 304 | 304 | 304 | 304 | 304 |
| Carista | 105,198 | 105,198 | 105,198 | 105,198 | 105,198 | 105,198 |
| Carly for BMW | 14,377 | 14,377 | 16,427 | 16,427 | 13,480 | 13,480 |
| Carly for Mercedes | 7,921 | 6,528 | 1,698 | 1,698 | 1,393 | 1,393 |
| Carly for Toyota | 5,305 | 5,266 | 39 | 39 | 39 | 39 |
| Carly for VAG | 16,402 | 7,283 | 18,627 | 10,429 | 7,283 | 7,283 |
| CarVantage | 41 | 41 | 41 | 41 | 41 | 41 |
| Engie | 144 | 144 | 68 | 68 | 68 | 68 |
| inCarDoc | 160 | 160 | 160 | 160 | 160 | 160 |
| Kiwi OBD | 220 | 220 | 6 | 6 | 6 | 6 |

Table: Part of the **cross-platform validation** (commands across different platforms) results.

# Correctness Evaluation

| App | Android | | iOS | | Overlapped | |
|---|---|---|---|---|---|---|
| | # Syn. | # Sem. | # Syn. | # Sem. | # Syn. | # Sem. |
| BlueDriver | 304 | 304 | 304 | 304 | 304 | 304 |
| Carista | 105,198 | 105,198 | 105,198 | 105,198 | 105,198 | 105,198 |
| Carly for BMW | 14,377 | 14,377 | 16,427 | 16,427 | 13,480 | 13,480 |
| Carly for Mercedes | 7,921 | 6,528 | 1,698 | 1,698 | 1,393 | 1,393 |
| Carly for Toyota | 5,305 | 5,266 | 39 | 39 | 39 | 39 |
| Carly for VAG | 16,402 | 7,283 | 18,627 | 10,429 | 7,283 | 7,283 |
| CarVantage | 41 | 41 | 41 | 41 | 41 | 41 |
| Engie | 144 | 144 | 68 | 68 | 68 | 68 |
| inCarDoc | 160 | 160 | 160 | 160 | 160 | 160 |
| Kiwi OBD | 220 | 220 | 6 | 6 | 6 | 6 |

Table: Part of the **cross-platform validation** (commands across different platforms) results.

# Correctness Evaluation

| App | Android | | iOS | | Overlapped | |
|---|---|---|---|---|---|---|
| | # Syn. | # Sem. | # Syn. | # Sem. | # Syn. | # Sem. |
| BlueDriver | 304 | 304 | 304 | 304 | 304 | 304 |
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Table: Part of the **cross-platform validation** (commands across different platforms) results.

# Correctness Evaluation

| Car model | # Overlapped | | App1 | App2 |
|---|---|---|---|---|
| | Android | iOS | | |
| Audi A4 | 52 | 52 | Carista | Carly for VAG |
| Audi A6 | 22 | 22 | Carista | Carly for VAG |
| Seat Leon | 19 | 19 | Carista | Carly for VAG |
| Skoda Fabia | 0 | 24 | Carista | Carly for VAG |
| VW Caddy | 0 | 12 | Carista | Carly for VAG |
| VW Polo | 52 | 52 | Carista | Carly for VAG |
| VW Tiguan | 8 | 0 | Carista | Carly for VAG |
| Skoda Superb | 0 | 20 | Carista | Carly for VAG |
| Porsche Cayenne | 0 | 72 | Carly for VAG | Carly for Partners |
| Toyota Prius | 39 | 39 | Carly for Toyota | Carista |
| BMW 550i | 8 | 8 | Carly for BMW | Carista |

Table: Part of the **in-platform validation** (commands within the same platforms) results

# Correctness Evaluation

| Car model | # Overlapped | | App1 | App2 |
|---|---|---|---|---|
| | Android | iOS | | |
| Audi A4 | 52 | 52 | Carista | Carly for VAG |
| Audi A6 | 22 | 22 | Carista | Carly for VAG |
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| VW Caddy | 0 | 12 | Carista | Carly for VAG |
| VW Polo | 52 | 52 | Carista | Carly for VAG |
| VW Tiguan | 8 | 0 | Carista | Carly for VAG |
| Skoda Superb | 0 | 20 | Carista | Carly for VAG |
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| VW Caddy | 0 | 12 | Carista | Carly for VAG |
| VW Polo | 52 | 52 | Carista | Carly for VAG |
| VW Tiguan | 8 | 0 | Carista | Carly for VAG |
| Skoda Superb | 0 | 20 | Carista | Carly for VAG |
| Porsche Cayenne | 0 | 72 | Carly for VAG | Carly for Partners |
| Toyota Prius | 39 | 39 | Carly for Toyota | Carista |
| BMW 550i | 8 | 8 | Carly for BMW | Carista |

Table: Part of the **in-platform validation** (commands within the same platforms) results

# Correctness Evaluation

A Toyota RAV4.

A Toyota Corolla.

# Correctness Evaluation

| Command (RAV4) | Command (Corolla) | Semantics |
|---|---|---|
| 750 ... 14 1A 26 | 750 ... 1A 65 02 | Wireless door locking |
| 750 ... 14 92 26 | 750 ... 92 65 02 | Blink turn signals |
| 750 ... 14 9A 06 | 750 ... 9A 45 02 | Panic Function on remote |
| 750 ... 14 9A 25 | 750 ... 9A 61 02 | Relock automatically |
| 750 ... 14 9A 26 | 750 ... 8A 65 02 | Beep when locking |
| 750 ... 11 00 60 | 750 ... 14 06 00 | Unlock via physical key |
| 750 ... 11 80 20 | 750 ... 11 C0 20 | Unlock when shifting into gear |
| 7C0 ... 3B A2 40 | 7C0 ... 3B A2 40 | Display unit (MPG) |
| 7C0 ... 3B 74 A0 | 7C0 ... 3B A7 C0 | Seat belt warning (driver) |
| 7CC ... 00 01 00 | 7CC ... 3B 82 00 | Fan Speed |

Table: Part of commands validated with **real-car testing**.

# Correctness Evaluation

| Command (RAV4) | Command (Corolla) | Semantics |
|---|---|---|
| 750 ... 14 1A 26 | 750 ... 1A 65 02 | Wireless door locking |
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| 7C0 ... 3B A2 40 | 7C0 ... 3B A2 40 | Display unit (MPG) |
| 7C0 ... 3B 74 A0 | 7C0 ... 3B A7 C0 | Seat belt warning (driver) |
| 7CC ... 00 01 00 | 7CC ... 3B 82 00 | Fan Speed |

Table: Part of commands validated with **real-car testing**.

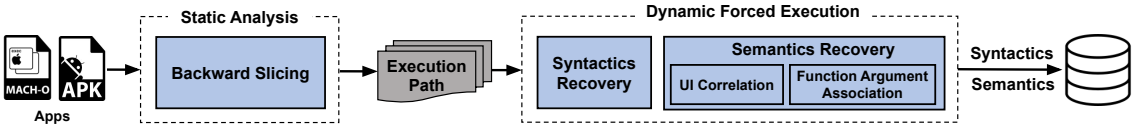
# Related Work

1. **CAN and Vehicle Security**.
   - Vehicle attack [MV14] [CMK+11] [MRHM16] [MV15] [Sta13] [MV13] and CAN reverse engineering [KCR+10].
   - Defenses of CAN bus. Anomaly detection [CS16] [MGF10] [NLJ08], forensics measures [HKD11] and delayed data authentication [NLJ08].
2. **Protocol Reverse Engineering**. Polyglot [CYLS07], AutoFormat [LJXZ08], Discoverer [CKW07], Tupni [CPC+08], and ReFormat [WJC+09].
3. **Forced execution**. J-Force [KKK+17] for JavaScript applications, X-Force [PDZ+14] and Limbo [WC07] for binaries, and Dexism [EJS18].

# Future Work

1. **Handling obfuscation**. The current implementation of CANHunter is not resilient to anti-analysis techniques such as control flow obfuscation. Deobfuscation techniques can be applied to address this limitation.
2. **Investigating other vehicle commands**. CANHunter reported a great number of AT commands for vehicle diagnosis, and also interpreted commands for vehicle control. These commands are worth of security attention.
3. **Reverse engineering of other IoT protocols**. CANHunter has the potential to be extended to reverse engineer the syntactics and semantics of other IoT protocols.

# CANHunter



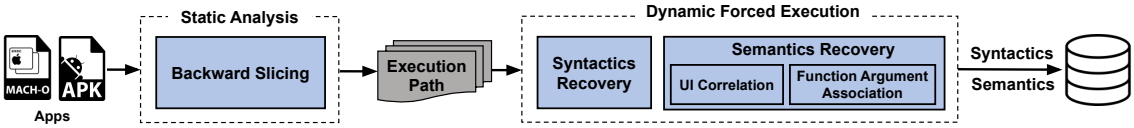

## CANHunter

- An automatic and cost-effective approach of reverse engineering CAN bus commands from mobile apps
- Recover both the syntactics and semantics of CAN bus commands

## Implementation and Evaluation

- We implemented CANHunter on both Android and iOS platforms
- We evaluated CANHunter on 236 apps in which 182,619 commands are discovered with 86% recovered with semantics

# CANHunter

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The source code and dataset is available at https://github.com/OSUSecLab/CANHunter.

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