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APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED
General Use Networks

- Modify End Points
- Modify Routing

No delivery guarantee
No timeliness guarantee

FLEXIBLE

UNDETERMINABLE

n end points
Control Networks

- Determinable: Delivery Guarantee, Timeliness Guarantee
- Inflexible: Fixed End Points, Fixed Routing

Meta Data: No Meta Data
Lots of people helping others play with general use networks...
Automated Reverse Engineering of General Use Networks


Automated Reverse Engineering of General Use Networks


But what about robots, cars, and other control networks?

Now your computer can help!

Hi! Do you need assistance?
# Started canhandler on can0
# Setup complete: 48.7387

# Format:

<table>
<thead>
<tr>
<th>Time</th>
<th>ID</th>
<th>DLC</th>
<th>Data</th>
</tr>
</thead>
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<td>020</td>
<td>7</td>
<td>00 00 07 01 00 00 2f</td>
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<td>48.742:</td>
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<td>8</td>
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<td>48.742:</td>
<td>025</td>
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<td>00 00 00 00 00 00 00 00</td>
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</tr>
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<td>49b</td>
<td>8</td>
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<td>262</td>
<td>5</td>
<td>00 00 00 89</td>
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<tr>
<td>48.747:</td>
<td>49d</td>
<td>8</td>
<td>61 60 00 00 9d 19 c6 c5</td>
</tr>
<tr>
<td>48.747:</td>
<td>1c4</td>
<td>8</td>
<td>00 00 00 00 00 00 00 cd</td>
</tr>
<tr>
<td>48.749:</td>
<td>0aa</td>
<td>8</td>
<td>1a 6f 1a 6f 1a 6f 1a 6f</td>
</tr>
<tr>
<td>48.749:</td>
<td>0b6</td>
<td>4</td>
<td>00 00 00 ba</td>
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<td>48.749:</td>
<td>224</td>
<td>8</td>
<td>00 00 00 00 00 00 00 08</td>
</tr>
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<td>8</td>
<td>68 10 00 08 00 0c ed a9</td>
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<td>020</td>
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<td>00 00 07 01 00 00 2f</td>
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<td>48.752:</td>
<td>025</td>
<td>8</td>
<td>00 11 00 00 82 82 82 c4</td>
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</table>

……..
Empirical Data Modeling to detect causality

Combine correlated and causal links to make a network map

Protocol Specific Preprocessing

Group Payloads by Logical Source

Lexical Analysis

TANG Generation

Cluster Payload Bit Positions

Semantic Analysis

Signal Correlation

Signal Subset Selection* *optional

Cluster Correlated Signals

Detect Causality Between Signals

Generate Logical Network Map

Exclusive Or (XOR)

Modified Hill Climbing Algorithm

Pearson’s Correlation Coefficient

Shannon Diversity Index (Entropy)

Agglomerative Hierarchical Clustering

Empirical Data Modeling to detect causality

Combine correlated and causal links to make a network map
Different Control Network Protocol?

Just change this →

- Protocol Specific Preprocessing
- Group Payloads by Logical Source

Lexical Analysis

TANG Generation

Cluster Payload Bit Positions

Semantic Analysis

Signal Correlation

Signal Subset Selection*

*optional

Cluster Correlated Signals

Detect Causality Between Signals

Generate Logical Network Map

- Exclusive Or (XOR)
- Modified Hill Climbing Algorithm
- Pearson’s Correlation Coefficient
- Shannon Diversity Index (Entropy)
- Agglomerative Hierarchical Clustering
- Empirical Data Modeling to detect causality
- Combine correlated and causal links to make a network map
The demo is doing this…

Empirical Data Modeling to detect causality

Combine correlated and causal links to make a network map

Protocol Specific Preprocessing

Group Payloads by Logical Source

Lexical Analysis

TANG Generation

Cluster Payload Bit Positions

Lexical Analysis

Cluster Correlated Signals

Detect Causality Between Signals

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Semantic Analysis

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Cluster Correlated Signals

Aggregate Hierarchical Clustering

Pearson’s Correlation Coefficient

Shannon Diversity Index (Entropy)

Disabled Data Modeling to detect causality

Combine correlated and causal links to make a network map

TANG Generation

Exclusive Or (XOR)

Modified Hill Climbing Algorithm

Exclusive Or (XOR)

Modified Hill Climbing Algorithm
I’ll walk you through this…

Empirical Data Modeling to detect causality
Combine correlated and causal links to make a network map

Lexical Analysis
Protocol Specific Preprocessing
Group Payloads by Logical Source

Semantic Analysis
Cluster Payload Bit Positions

TANG Generation

Exclusive Or (XOR)
Modified Hill Climbing Algorithm

Pearson’s Correlation Coefficient
Shannon Diversity Index (Entropy)
Agglomerative Hierarchical Clustering
Empirical Data Modeling to detect causality
Combine correlated and causal links to make a network map

Detect Causality Between Signals
Generate Logical Network Map
Unsupervised Reverse Engineering

Empirical Data Modeling to detect causality
Combine correlated and causal links to make a network map

Lexical Analysis
Protocol Specific Preprocessing
Group Payloads by Logical Source
Semantic Analysis

TANG Generation

Cluster Payload *Bit Positions*

Exclusive Or (XOR)
Modified Hill Climbing Algorithm

Pearson’s Correlation Coefficient
Shannon Diversity Index (Entropy)
Agglomerative Hierarchical Clustering
Empirical Data Modeling to detect causality
Combine correlated and causal links to make a network map

Cluster Correlated Signals
Detect Causality Between Signals
Generate Logical Network Map

*optional
Lexical & Semantic Analysis

This is a sentence!
Lexical Analysis

This is a sentence!

Tokens
Semantic Analysis

This is a sentence!

Token Type

noun
### 64-bit Payloads

<table>
<thead>
<tr>
<th>Time</th>
<th>Bit 0</th>
<th>Bit 63</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.45</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>48.95</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>49.46</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>49.96</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.46</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.96</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Lexical Analysis

Payload Tokenization

This is a sentence!
### 64-bit Payloads

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<th>Bit 0</th>
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<td>0</td>
</tr>
<tr>
<td>50.46</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.96</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

---

**Lexical Analysis**

**Payload Tokenization**

[Graph showing time (s) against payload bits]

- Time: 50 to 250 seconds
- Payloads represented as 1's and 0's for each bit position.
Lexical Analysis
Payload Tokenization

<table>
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<th>Time</th>
<th>Bit 0</th>
<th>Bit 63</th>
</tr>
</thead>
<tbody>
<tr>
<td>48.45</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>48.95</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>49.46</td>
<td>1</td>
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<tr>
<td>49.96</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.46</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.96</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

This is a sentence!
## Lexical Analysis

### Payload Tokenization

### 64-bit Payloads

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<th>Bit 0</th>
<th>Bit 63</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>49.46</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>49.96</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.46</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50.96</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

![Graphs showing time series from bit positions 0 to 31, 16 to 31, and 32 to 39 of Arb ID 0x4a0.](image-url)
Payload Tokenization
By Least Significant Bit

<table>
<thead>
<tr>
<th>Bit Position</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Payloads</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0 1 1 1</td>
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<td>0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 0 0 0</td>
<td>0 0 0 0</td>
<td>0 0 0 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0 0 0 0</td>
<td>0 1 0 0</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0 0 0 0</td>
<td>0 1 1 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 0 1 1</td>
<td>0 0 0 0</td>
<td>1 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1 0 0</td>
<td>0 0 0 0</td>
<td>1 0 1 0</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1 0 1</td>
<td>0 0 0 0</td>
<td>1 1 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 1 1 0</td>
<td>0 0 0 0</td>
<td>1 1 1 1</td>
<td></td>
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<td></td>
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<tr>
<td>1 1 1 1</td>
<td>0 0 0 0</td>
<td>1 1 1 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Payload Tokenization
By Least Significant Bit

Bit Position: 0 1 2 3 4 5 6 7 8 9

Exclusive-OR gate

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
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<td>1</td>
</tr>
<tr>
<td>1</td>
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<td>1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

payload tokenization by least significant bit
# Payload Tokenization

By Least Significant Bit

## Bit Position:

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output</strong></td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

**Exclusive-OR gate**

<table>
<thead>
<tr>
<th>Input A</th>
<th>Input B</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0</td>
<td>0</td>
<td>0</td>
</tr>
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<td>0 1</td>
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<td>1 0</td>
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<td>1 1</td>
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<table>
<thead>
<tr>
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<th>1</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
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<th>1</th>
</tr>
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<tbody>
<tr>
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<td>0 0</td>
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<td>0 0</td>
<td>0 0</td>
<td>0 1</td>
<td>1 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 0</td>
<td>0 1</td>
<td>1 1</td>
<td>0 0</td>
<td>0 0</td>
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<tr>
<td>0 0</td>
<td>0 0</td>
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<td>0 1</td>
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</tr>
<tr>
<td>0 0</td>
<td>0 0</td>
<td>1 1</td>
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<td>0 0</td>
<td>0 0</td>
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<td>0 0</td>
<td>0 1</td>
<td>1 1</td>
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<td>0 0</td>
<td>0 1</td>
<td>1 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Bit Position* refers to the position of the Bit inside the Payload Tokenization system.
## Payload Tokenization

### By Least Significant Bit

### Bit Position: 0 1 2 3 4 5 6 7 8 9

<table>
<thead>
<tr>
<th>Bit Position</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

**Payload Tokenization**

Add the values in the bit positions indicated by the sum of the least significant bit positions:

<table>
<thead>
<tr>
<th>Bit Position</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</tr>
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<tbody>
<tr>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>3</td>
<td>7</td>
</tr>
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</table>
Payload Tokenization
By Least Significant Bit
Unsupervised Reverse Engineering

- Empirical Data Modeling to detect causality
- Combine correlated and causal links to make a network map

Lexical Analysis
- Protocol Specific Preprocessing
- Group Payloads by Logical Source

TANG Generation
- Signal Correlation
- Signal Subset Selection* (optional)
- Cluster Correlated Signals
- Detect Causality Between Signals
- Generate Logical Network Map

Cluster Payload Bit Positions
- Exclusive Or (XOR)
- Modified Hill Climbing Algorithm

Semantic Analysis
- Pearson’s Correlation Coefficient
- Shannon Diversity Index (Entropy)
- Agglomerative Hierarchical Clustering
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By Least Significant Bit
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Lexical Analysis
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Cluster Correlated Signals
Detect Causality Between Signals
Generate Logical Network Map

Modified Hill Climbing Algorithm
Exclusive Or (XOR)

Pearson’s Correlation Coefficient
Shannon Diversity Index (Entropy)
Agglomerative Hierarchical Clustering
Empirical Data Modeling to detect causality
Combine correlated and causal links to make a network map

*optional
Semantic Analysis
Correlated and Causal Relationships

SHOW ME WHAT YOU GOT!

Let’s reverse engineer some cars!

https://github.com/brent-stone/CAN_Reverse_Engineering
VEHICLE 1

VEHICLE 2

Signal Cluster 21 from Vehicle 1

Time Series from Bit Positions 9 to 15 of Arb ID 0x348

Time Series from Bit Positions 16 to 31 of Arb ID 0x348

Time Series from Bit Positions 0 to 15 of Arb ID 0x34e

Time Series from Bit Positions 16 to 31 of Arb ID 0x34e

Time Series from Bit Positions 0 to 15 of Arb ID 0x2e9

Time Series from Bit Positions 16 to 31 of Arb ID 0x2e9

Time Series from Bit Positions 0 to 15 of Arb ID 0x3e9

Time Series from Bit Positions 16 to 31 of Arb ID 0x3e9

https://github.com/brent-stone/CAN_Reverse_Engineering
VEHICLE 5

Time Series from Bit Positions 0 to 15 of Arb ID 0x76

Time Series from Bit Positions 0 to 31 of Arb ID 0x3a8

VEHICLE 6

Time Series from Bit Positions 0 to 15 of Arb ID 0x215

Time Series from Bit Positions 16 to 31 of Arb ID 0x215

Time Series from Bit Positions 32 to 47 of Arb ID 0x215

Time Series from Bit Positions 48 to 63 of Arb ID 0x215

Time Series from Bit Positions 16 to 47 of Arb ID 0x201

https://github.com/brent-stone/CAN_Reversal_Engineering
**VEHICLE 7**

![Time Series from Bit Positions 0 to 15 of Arb ID 0x138](image1)

![Time Series from Bit Positions 32 to 47 of Arb ID 0x138](image2)

![Time Series from Bit Positions 48 to 59 of Arb ID 0x138](image3)

![Time Series from Bit Positions 0 to 14 of Arb ID 0x140](image4)

![Time Series from Bit Positions 13 to 29 of Arb ID 0x140](image5)

![Time Series from Bit Positions 30 to 44 of Arb ID 0x140](image6)

![Time Series from Bit Positions 45 to 63 of Arb ID 0x140](image7)

![Time Series from Bit Positions 48 to 55 of Arb ID 0x140](image8)

**VEHICLE 8**

![Time Series from Bit Positions 0 to 15 of Arb ID 0x138](image9)

![Time Series from Bit Positions 18 to 47 of Arb ID 0x138](image10)

![Time Series from Bit Positions 48 to 59 of Arb ID 0x138](image11)

![Time Series from Bit Positions 0 to 14 of Arb ID 0x140](image12)

![Time Series from Bit Positions 13 to 29 of Arb ID 0x140](image13)

![Time Series from Bit Positions 30 to 44 of Arb ID 0x140](image14)

![Time Series from Bit Positions 45 to 63 of Arb ID 0x140](image15)

![Time Series from Bit Positions 0 to 47 of Arb ID 0x109](image16)

CROPPED TO FIT ON SLIDE

https://github.com/brent-stone/CAN.Reverse.Enginering
VEHICLE 9

Signal Cluster 17 from Vehicle 8

Time Series from Bit Positions 0 to 15 of Arb ID 0x158

Time Series from Bit Positions 32 to 47 of Arb ID 0x158

Time Series from Bit Positions 0 to 43 of Arb ID 0x188

Time Series from Bit Positions 0 to 14 of Arb ID 0x1d0

Time Series from Bit Positions 15 to 28 of Arb ID 0x1d0

Time Series from Bit Positions 20 to 39 of Arb ID 0x1d0

Time Series from Bit Positions 45 to 63 of Arb ID 0x1d0

VEHICLE 10

Time Series from Bit Positions 0 to 15 of Arb ID 0x353

Time Series from Bit Positions 0 to 15 of Arb ID 0x180

Time Series from Bit Positions 0 to 15 of Arb ID 0x354

Time Series from Bit Positions 0 to 15 of Arb ID 0x285

Time Series from Bit Positions 32 to 35 of Arb ID 0x285

Time Series from Bit Positions 32 to 35 of Arb ID 0x285

Time Series from Bit Positions 32 to 35 of Arb ID 0x285

Time Series from Bit Positions 28 to 32 of Arb ID 0x284

https://github.com/brent-stone/CAN_Reverse_Engineering

CROPPED TO FIT ON SLIDE
VEHICLE 15

**Signal Cluster 26 from Vehicle 15**

Time Series from Bit Positions 0 to 15 of Arb ID 0x1c4

Time Series from Bit Positions 0 to 15 of Arb ID 0x1d0

Time Series from Bit Positions 0 to 63 of Arb ID 0x1ea

Time Series from Bit Positions 0 to 23 of Arb ID 0x498

Time Series from Bit Positions 0 to 15 of Arb ID 0x3b3

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VEHICLE 16

**Signal Cluster 26 from Vehicle 15**

Time Series from Bit Positions 0 to 15 of Arb ID 0x1c4

Time Series from Bit Positions 0 to 15 of Arb ID 0x1d0

Time Series from Bit Positions 0 to 63 of Arb ID 0x1ea

Time Series from Bit Positions 0 to 23 of Arb ID 0x498

Time Series from Bit Positions 0 to 15 of Arb ID 0x3b3

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https://github.com/brent-stone/CAN_Reverse_Engineering
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