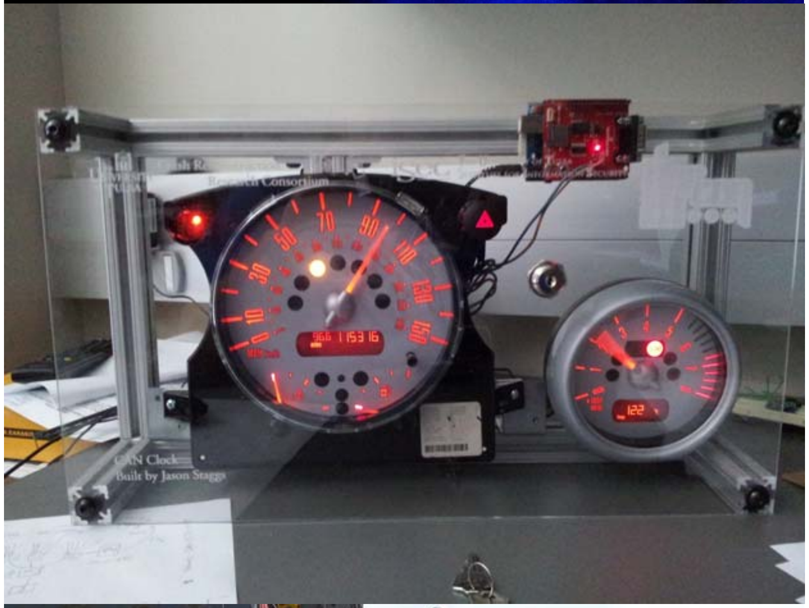
Jason Staggs - CAN Clock

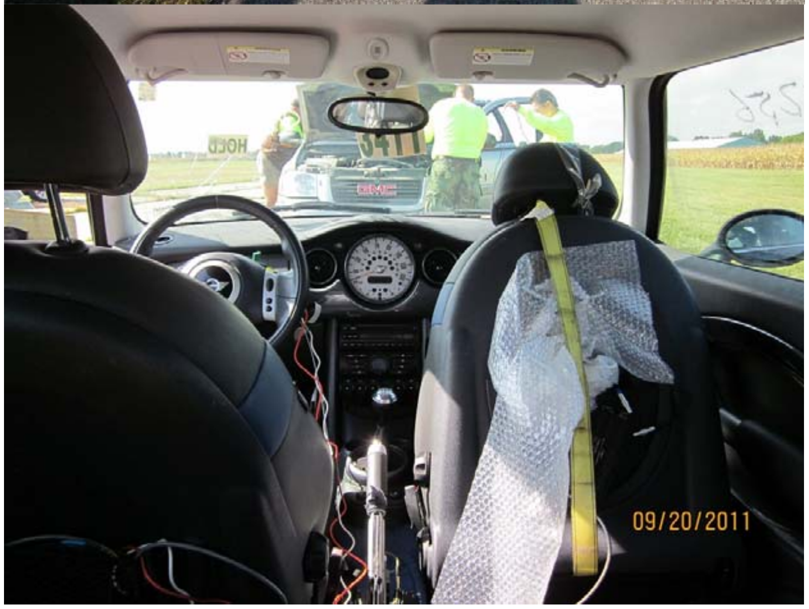
From Research Wiki

Contents

CAN Clock

This page serves as the documentation for the CAN Clock research project that was conducted as a result of the Vehicle Communication Systems class that was led by Dr. Jeremy Daily, and Dr. Mauricio Papa during the spring of 2013 at The University of Tulsa. This article assumes the user has a general understanding of conventional networking, along with a basic understanding of Controller Area Networks (CAN). This research describes a method for reverse engineering CAN messages on passenger automobiles by visually correlating physical system interactions with identifiable patterns. The methods used for identifying these messages were used to construct a fully functional CAN based clock. The clock was composed of an instrument cluster from a 2003 MINI Cooper S where the speedometer and tachometer were leveraged. The clock is controlled by CAN messages sent over a CAN network. The Speedometer is used as the hour hand of the clock, with the range of 10-120 MPH used as 1:00-12:00. Similarly, the tachometer range of 0-6000 RPM is used for the 0-60 minute range of the minute hand. Note: The instrument cluster used in this project was from a wrecked MINI Cooper that was involved in a staged auto collision with a GMC Envoy.


CAN Clock
Built by Jason Staggs



Introduction

Motivation

Designed as a multimaster broadcast serial bus to interconnect embedded systems within automobiles, such as Electronic Control Units (ECUs), CAN is the defacto standard for communication among devices within a vehicle network. The CAN protocol stack and subsequent devices that reside on CAN networks have been designed with safety, and reliability being the utmost priority. However, little efforts have been put into the security of such networks. This is especially alarming if a CAN node becomes under adversarial control, placing the rest of the components on the network at risk. The CAN Clock proof of concept demonstrates the ease in which an attacker could take control of other, more serious components, such as safety critical devices.

Objective

The primary objective for this project is to convert the instrument cluster pack of the MINI Cooper into a functional clock. In order to meet this primary objective, several secondary objectives had to be met. They include the following:

- Identify CAN message IDs that are associated with controlling the speedometer and tachometer on the instrument cluster.
- Identify which byte/s offsets are responsible for vehicle and engine speed.
- Build CAN network from scratch
- Program Arduino Microcontroller

Procedure

Reverse Engineering CAN IDs

This section describes a methodology for reverse engineering proprietary CAN message IDs on passenger vehicles. Since BMW does not publicly disclose CAN message IDs for ECUs used in their vehicles, a method is needed for reverse engineering these IDs. Several methods can be used for reverse engineering proprietary CAN IDs, they include:

- Visually identifying physical automotive events by plotting message data versus time
- Fuzzing data fields of known message IDs (*DANGER WILL ROBINSON!)
- Static analysis (identifying the actual source of a message by removing individual fuses)

The first method can be used to help identify messages that are reporting physical events of the vehicle, such as vehicle/engine speed. Messages can be plotted with either individual bytes, or a combination of bytes from a message versus time stamps. This would allow subjects analyzing the graphs to visually recognize any sort of obvious plotting trends that were representative of the pattern expected. External measurement devices, such as the VBOX (Velocity Box), can be used to cross reference actual measurements such as speed, to the actual CAN traffic that was recorded on the CAN bus. The VBOX is a high accuracy GPS data logging device. This is an excellent way to verify messages related to speed coming off of the CAN bus.

The second method is an excellent way of identifying byte/s offsets of individual CAN messages that are designed to control CAN components. If a CAN message has been narrowed down or isolated but the data fields of interest are still in question, fuzzing these fields can help determine the physical significance of the message and data field combination. Note: This method can be EXTREMELY DANGEROUS, especially if attempted during the live operation of a vehicle.

Alternatively, the third method can be used to identify the source component of a CAN message. By monitoring CAN traffic with something like the Vector CANAlayzer, one can manually begin to individually remove fuses from the automobiles fuse box to help isolate/determine the likely actual source of the CAN message. An example of such a case could include hypothesizing the ECU source of a CAN message. By individually removing fuses and simultaneously watching the CAN traffic to see which messages disappear, one can then begin to determine the likely source of a CAN message.

Unique Messages on CAN bus

To passively capture the traffic coming off of the CAN bus, a Gryphon S3 data logging device was used to capture all the traffic. The table below shows all of the messages that were broadcast over the MINI Cooper CAN bus during the staged auto collision.

MINI Cooper CAN Messages

CAN ID (Decimal)	CAN ID (HEX)
339	0x153
496	0x1F0
499	0x1F3
501	0x1F5
504	0x1F8
790	0x316
809	0x329
822	0x336
1349	0x545
235	0x565
1555	0x613
1557	0x615
1560	0x618
1562	0x61A
1567	0x61F

Examining the CAN Capture

Now that we have our data capture from the CAN bus. We need to apply these methods of reverse engineering the CAN IDs in order to tie actual CAN messages to components, and component functionality. We will start off by looking for messages that are indicative of vehicle speed. We can do this by programmatically plotting individual bytes of the data fields versus time from CAN messages as show below. This can be done in a variety of ways including using simple scripts such as Bash/gnuplot, Python, Microsoft Excel, etc.

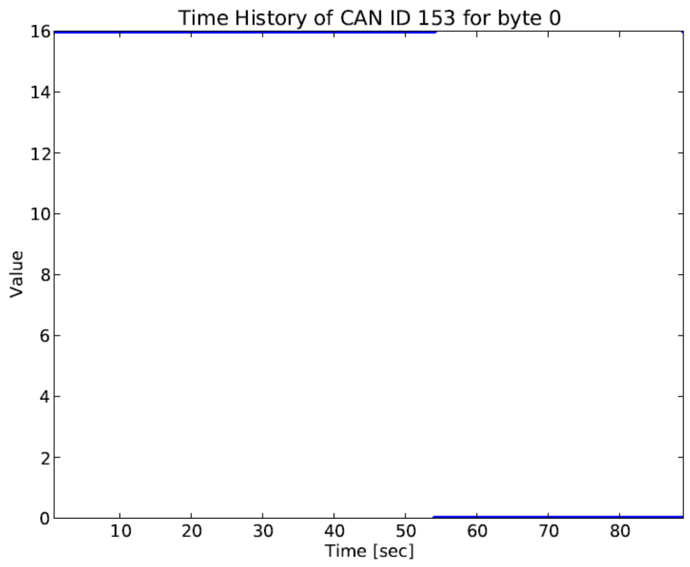
We start by plotting messages that were transmitted more frequently over the CAN bus during the data capture. Note: A total of 106,600 messages were actually transmitted over the course of ~90 seconds.

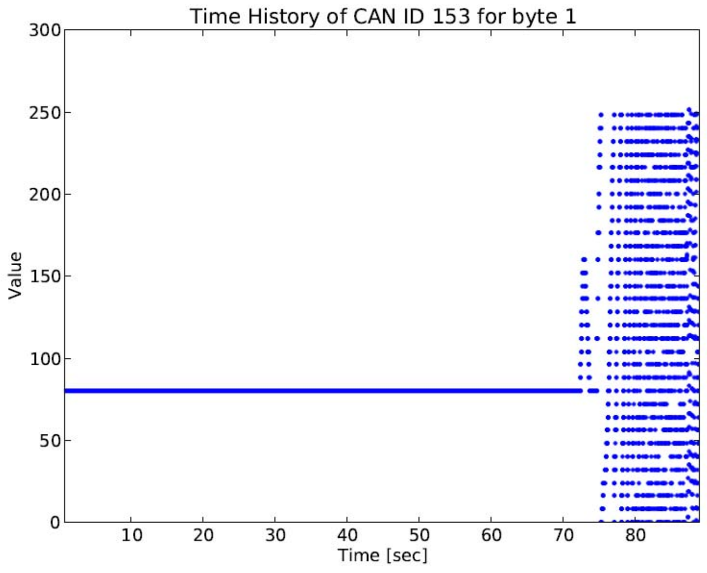
Frequency of Messages

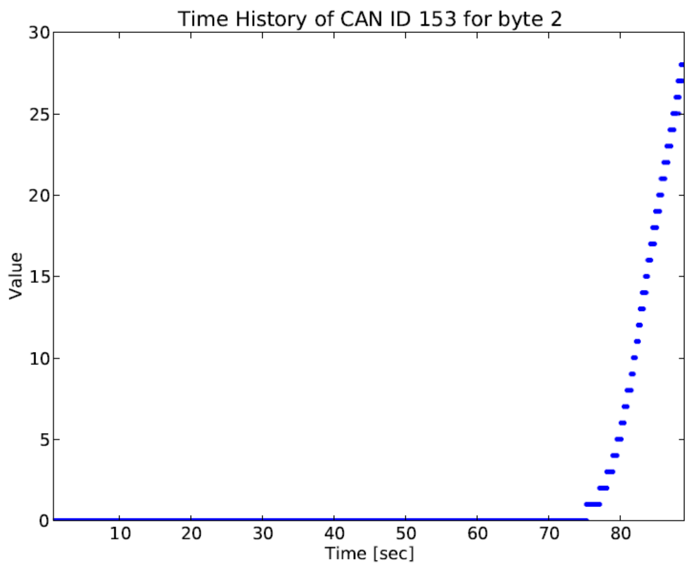
Message Frequency	CAN IDs
12706	0x153
12706	0x1F0
12706	0x1F3
9460	0x1F5
12707	0x1F8
8899	0x316
8899	0x329
8899	0x336
8899	0x545
8899	0x565

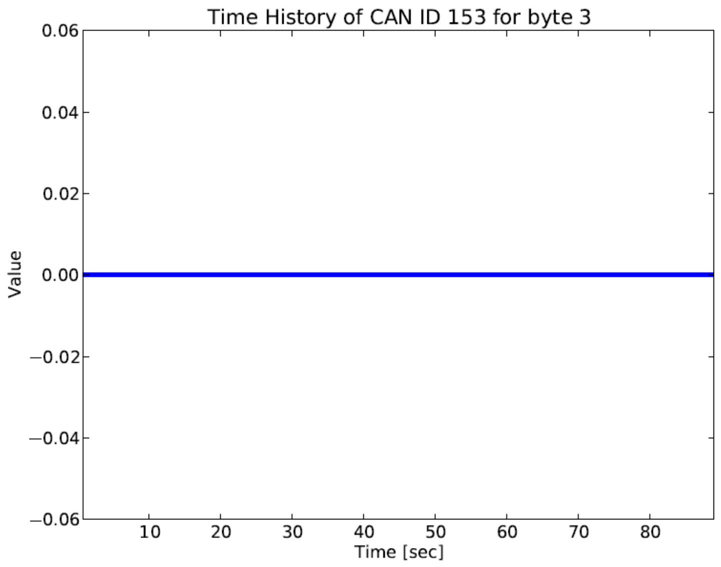
433	0x613
433	0x615
433	0x618
434	0x61A
87	0x61F

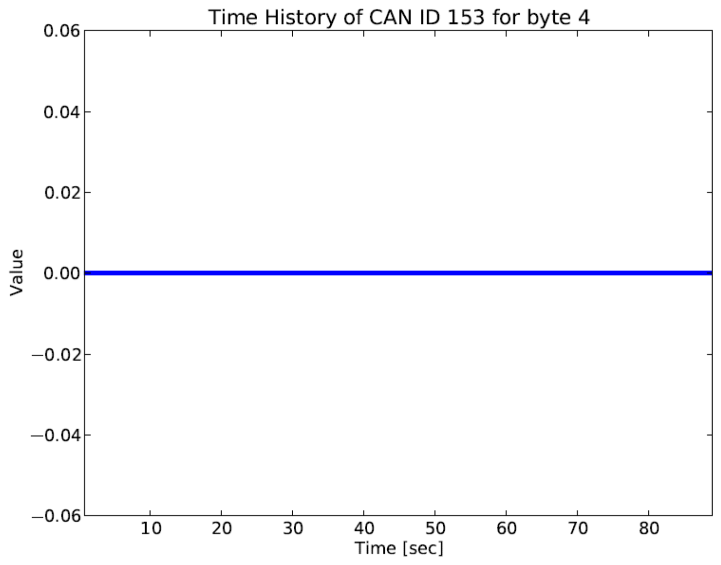
***Message ID 0x153** The images below were produced using a Python script(link to Dr. Daily's script) that is designed to parse the CAN data log produced by the Gryphon S3.

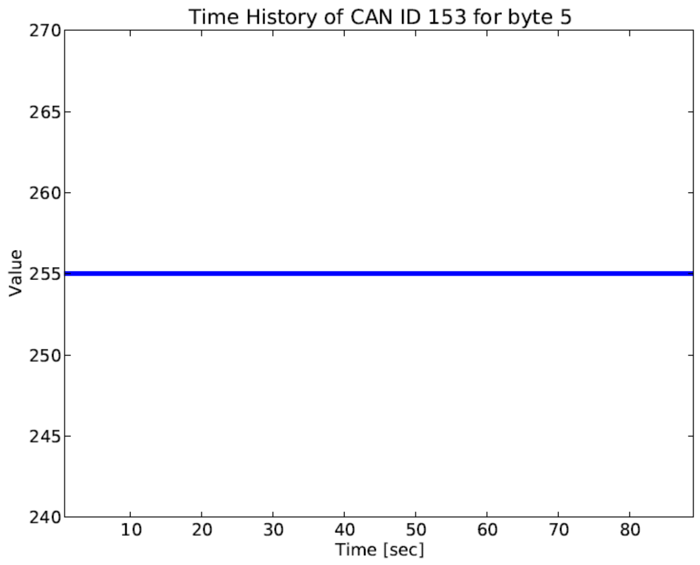


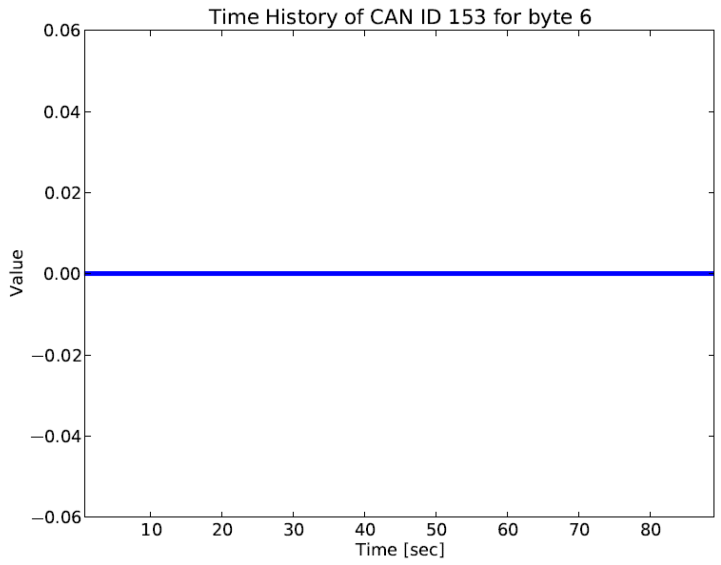


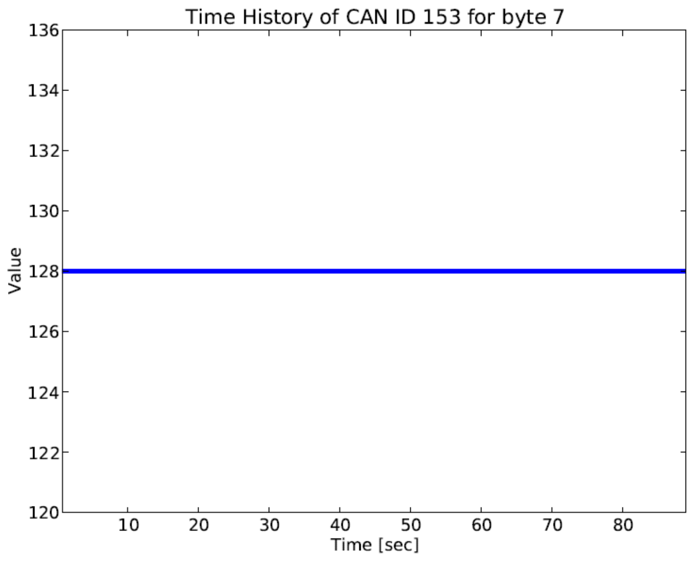

Time History of CAN ID 153 for byte 2
Value
Time [sec]
0
5
10
15
20
25
30
10
20
30
40
50
60
70
80


Time History of CAN ID 153 for byte 3
Value
Time [sec]
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
10
20
30
40
50
60
70
80

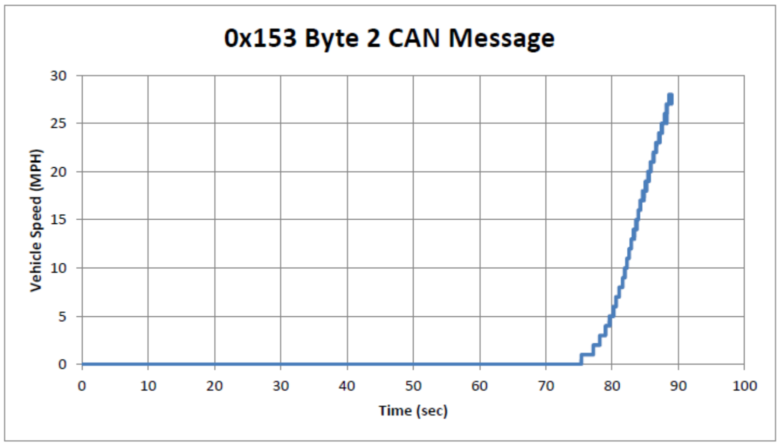

Time History of CAN ID 153 for byte 4
Value
Time [sec]
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
10
20
30
40
50
60
70
80







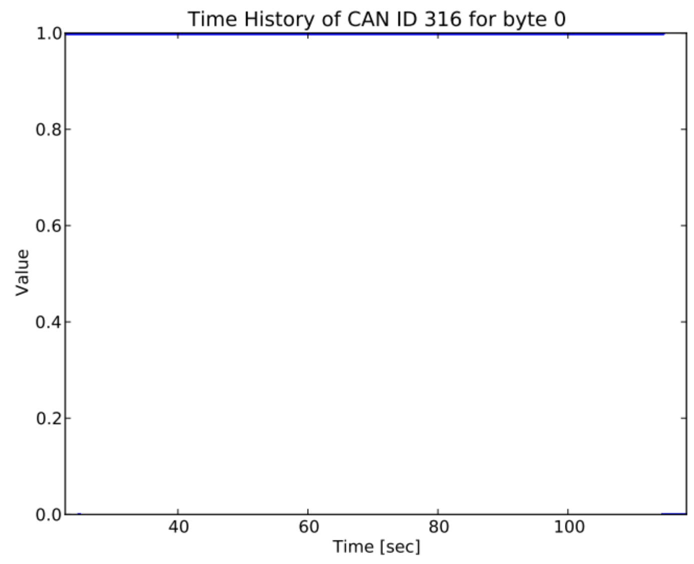
As we can see, message ID 0x153 byte 2 of the data field shows a consistent increase over the duration of the capture during the staged auto collision which lasted roughly 90 seconds. This increase is most indicative of vehicle speed, as we know with external instrument measurements that the speed of the MINI Cooper just before impact was nearing 30 MPH. Note: Other messages were also found to be indicative of vehicle speed, these messages were likely from individual wheel sensors. However, these messages were not responsible for controlling the speedometer directly.

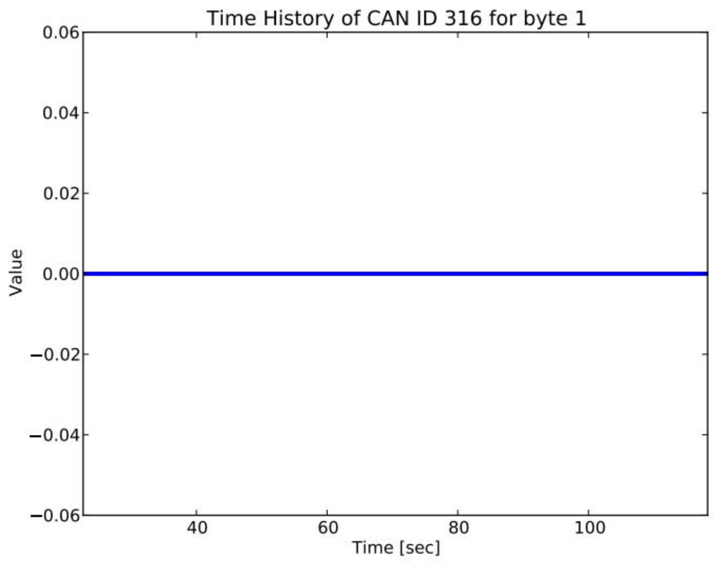


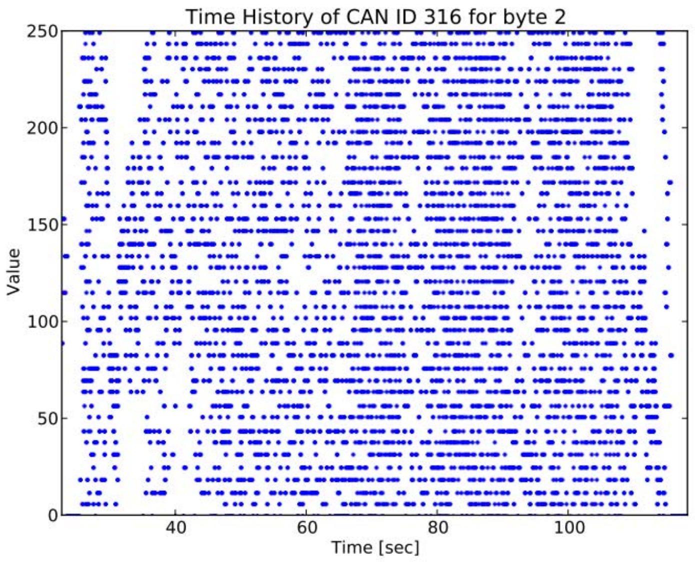
***CAN message used to manipulate speedometer.**

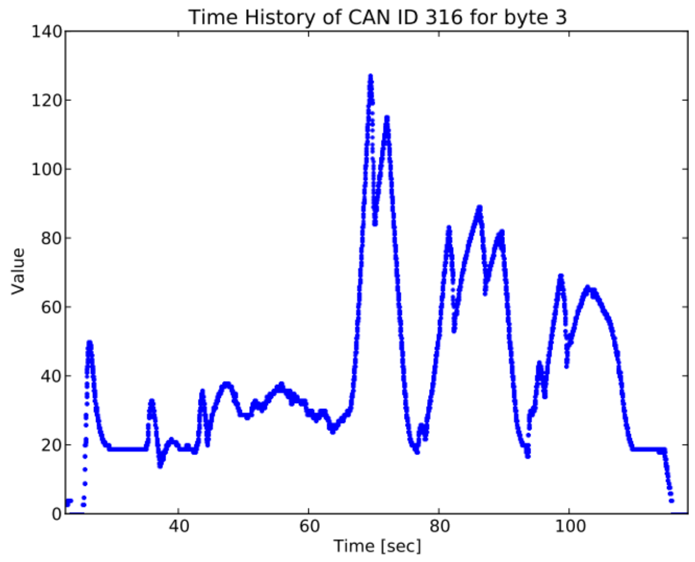
Now that we have identified the message ID and byte offset for vehicle speed, we need to isolate the ID and data fields for engine speed. Because the MINI Cooper was propelled with a pulley system in the staged crash in which the data log was recorded, the actual engine speed was at a constant idle speed throughout the capture. Because of the engine speed being idle during the experiment, our previous method of visually identifying message IDs based on data value against timestamps will be ineffective for identifying this message ID with this data set. Instead, we will use a data log capture from a previous test run of the MINI Cooper. In this test the driver performed a variety of skid tests within the confines of a controlled environment. Below are the results of that data run in which we were able to visually identify engine like speed.

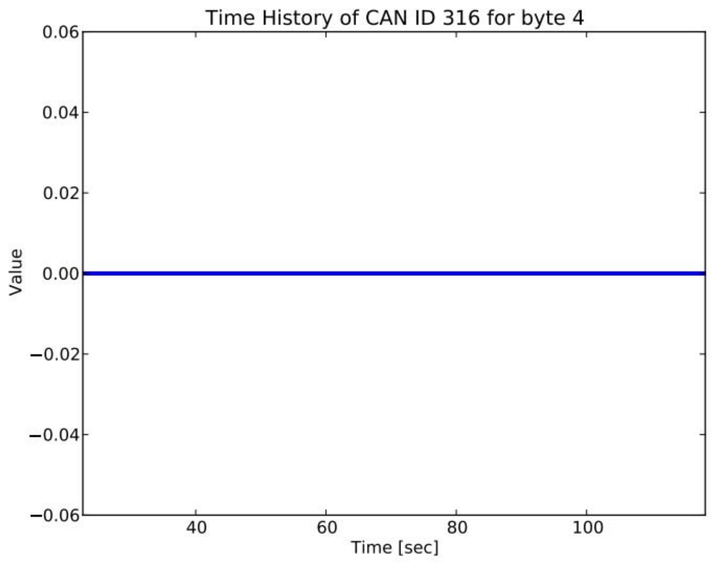
***Message ID 0x316**

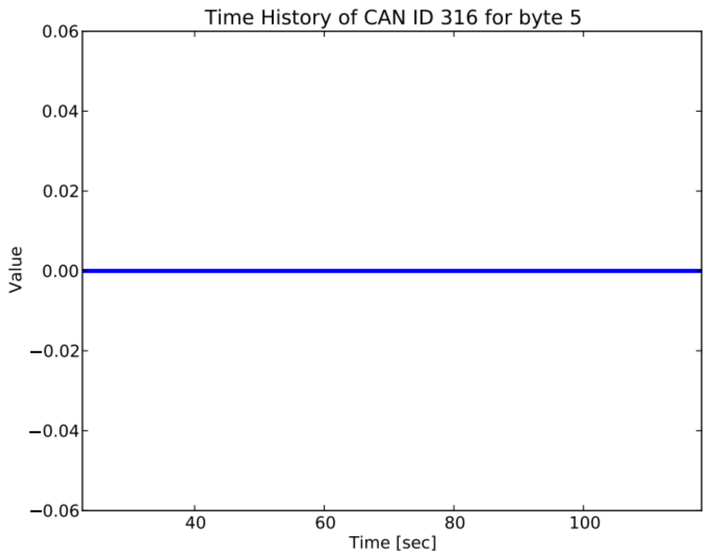


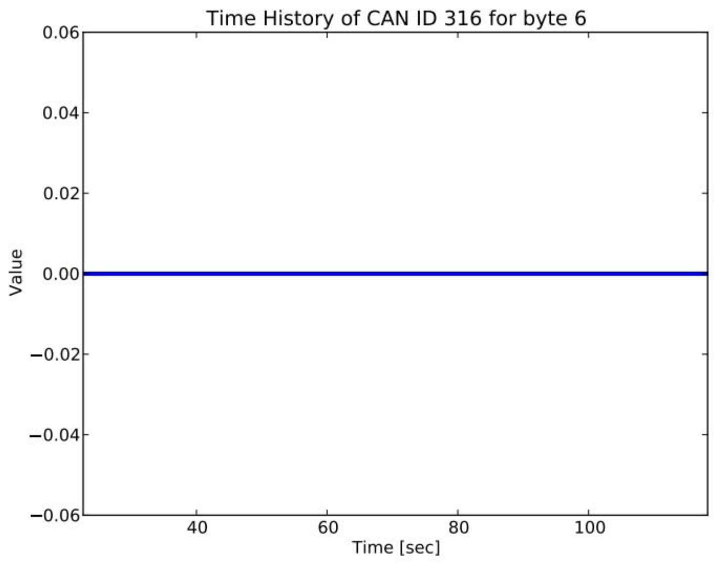

Time History of CAN ID 316 for byte 1
Value
Time [sec]
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
40
60
80
100

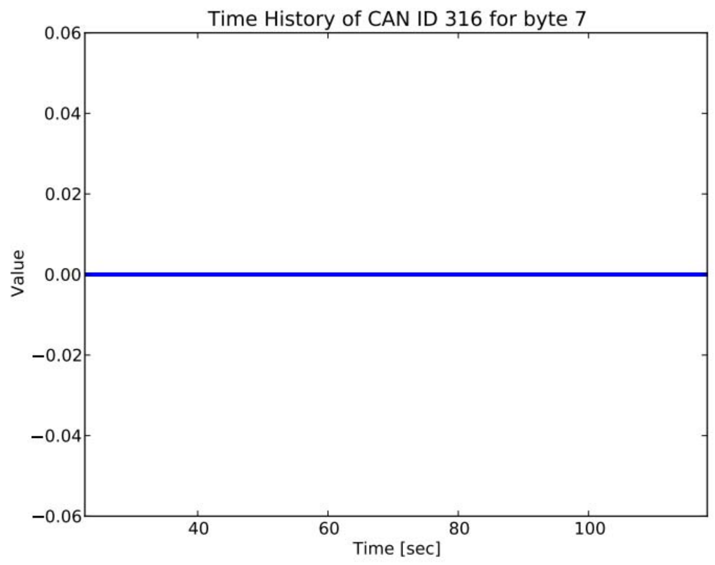

Time History of CAN ID 316 for byte 2
Value
Time [sec]
250
200
150
100
50
0
40
60
80
100


Time History of CAN ID 316 for byte 3
Value
Time [sec]
140
120
100
80
60
40
20
0
40
60
80
100


Time History of CAN ID 316 for byte 4
Value
Time [sec]
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
40
60
80
100


Time History of CAN ID 316 for byte 5
Value
Time [sec]
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
40
60
80
100


Time History of CAN ID 316 for byte 6
Value
Time [sec]
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
40
60
80
100



One of the more interesting things to measure and verify is vehicle speed. It is normal to see multiple messages and or byte offsets that are representative of vehicle speed. Vehicle wheel speed sensors on the car can report varying wheel speeds because of various physical interactions. This could include wheel slip, ice, etc. Although these sensors are transmitting wheel speed, they are not necessarily the messages that are being transmitted to the speedometer on the instrument cluster. For this reason, we are only interested in the vehicle speed being reported to the speedometer of the instrument cluster.

There are 15 unique IDs in the log file that are summarized in the following table. The timing data in the table below is approximate. Byte counts start at 0 and go to 7 for an 8 byte message.

Identified CAN Messages

CAN ID (HEX)	Frequency (Hz)	Period (sec.)	Notes
0x153	142.756	0.00700497	Vehicle speed like message in byte 2. Byte 2 is used to manipulate Speedometer.
0x1F0	142.756	0.00700497	
0x1F3	142.756	0.00700497	
0x1F5	106.296	0.00940773	
0x1F8	142.756	0.00700497	
0x316	99.9789	0.0100021	
0x329	99.9789	0.0100021	Various indicator lights
0x336	99.9789	0.0100021	
0x545	99.9902	0.010001	
0x565	99.9902	0.010001	
0x613	4.86513	0.205545	Message deals with tachometer functionality. Byte 3 is used to control the tachometer directly.
0x615	4.86513	0.205545	
0x618	4.86513	0.205545	
0x61A	4.87647	0.205067	Controls the messages being displayed on the tachometer LED screen.

0x61F	0.975293	1.02533	Tachometer along with various indicator lights.

CAN Clock Proof of Concept

In this section we describe the steps in creating/building the CAN Clock proof of concept that simulates the effect an attacker could have on a vehicle, assuming she has physical access. In this demonstration we transform the speedometer and a tachometer from a wrecked 2003 MINI Cooper S into a literal clock, where the hours will be represented by the speedometer (0-120 MPH) and the minutes will be represented by the tachometer (0-6000 RPM). We build a CAN network with three physical CAN nodes. We generate CAN traffic by building a CAN ECU using an Arduino microcontroller, MCP1215 CAN controller, and MCP2551 CAN transceiver.

The following hardware, software, and tools were used to construct the CAN Clock:

Hardware Supplies

- 2003 Mini Cooper S instrument cluster module(IKE)"This is actually the unit housing the speedometer"
- 2003 Mini Cooper S tachometer
- Arduino Uno "Using REV 3 in this tutorial"
- CAN-BUS Shield for Arduino Uno "Available from sparkfun.com"
- 2 x 120 ohms resistor
- 18 gauge twisted pair wire "For CAN bus backbone"
- Wire nuts
- Tie wraps
- 12V DC power source
- 2 x 1.5" x 1.625" x 1.25" brackets with bolts

Tools

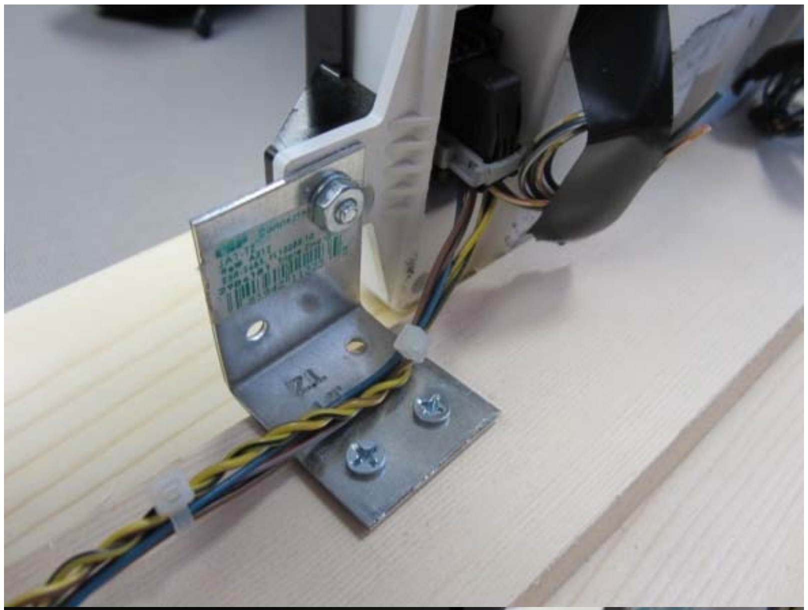
- Wire strippers
- Solder
- Soldering iron

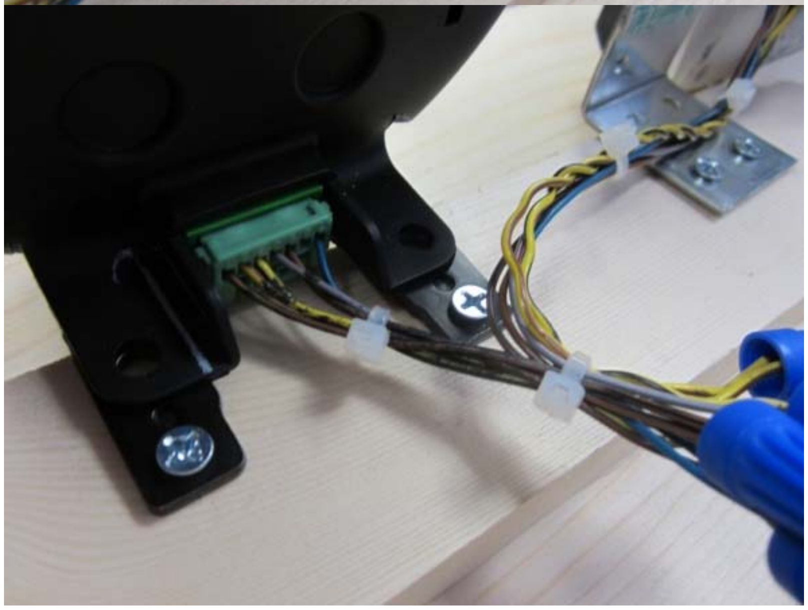
Software

- Python/Bash
- Microsoft Excel

Tutorial

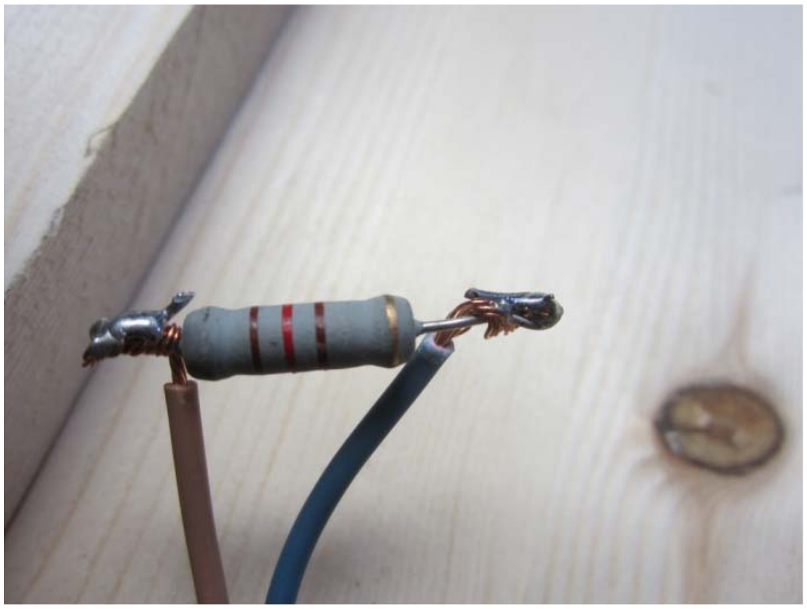
Initially the hardware was mounted onto a self-contained board. For prototyping purposes a 18” x 14” wood board was used to house the platform of the CAN Clock. Next, the MINI Cooper gauges were mounted using brackets, screws, and bolts.





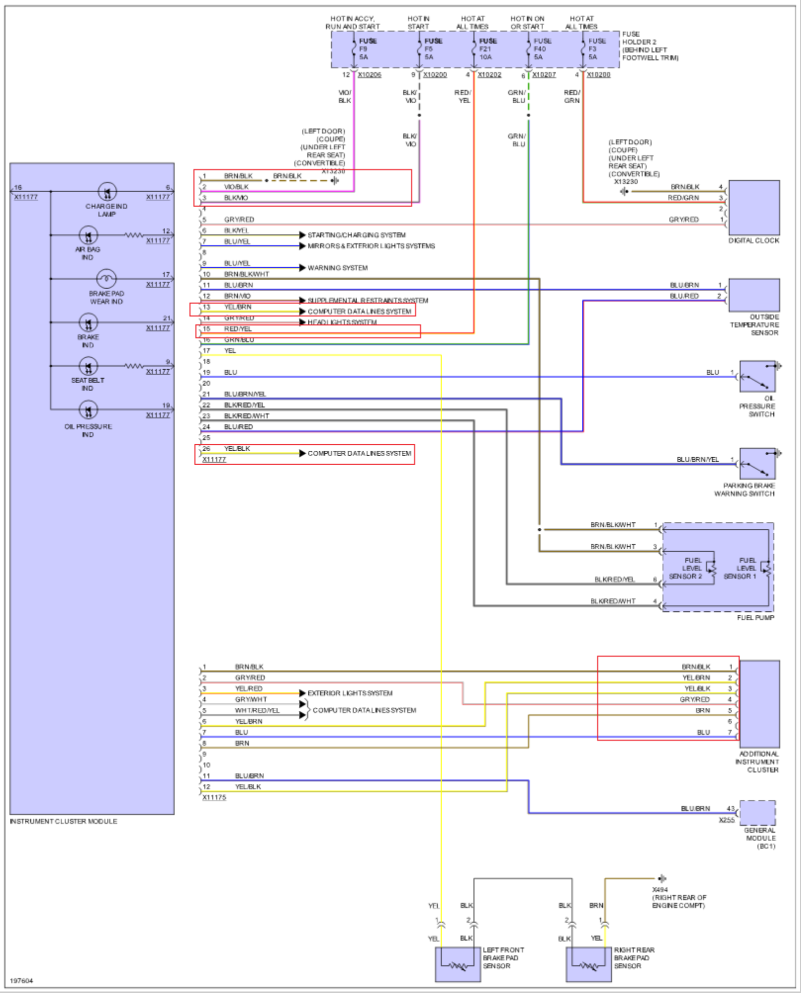
Since BMW does not publicly disclose CAN message IDs for their various ECU devices on passenger vehicles, we applied our reverse engineering methodology described above. Using this methodology, we now have a pretty solid idea of what message IDs and byte offsets are needed to control the display of the speedometer and tachometer on the instrument cluster. The next step is building a small CAN network and a CAN node capable of introducing messages onto the data bus. The first thing we need to do is build the CAN bus infrastructure. In adhering to the CAN standard, we used about 18 inches of 18 gauge twisted pair wire for the actual CAN bus backbone.

We also terminate both ends of the twisted pair wire by using 120 Ω terminating resistors at each end to reduce reflection.



We now have the CAN bus backbone built and ready to add nodes onto it. Next we attach the MINI Cooper instrument cluster (which includes both the speedometer and tachometer) onto the network via its CAN data lines. When attempting to modify hardware that is either unfamiliar or unknown, the first thing that should be done is referencing the electrical schematics, if they are available. In this case we were able to utilize the MINI Cooper electrical schematics from Mitchell (www.prodemand.com). Mitchell maintains an enormous repository full of vehicle service manuals, diagnostic codes, and wiring schematics for a majority of passenger vehicles. Leveraging this information was necessary for identifying the wires coming off of the instrument cluster units.

The wires of interest have been highlighted in the image below.



Instrument Cluster Circuit

Wires associated with power

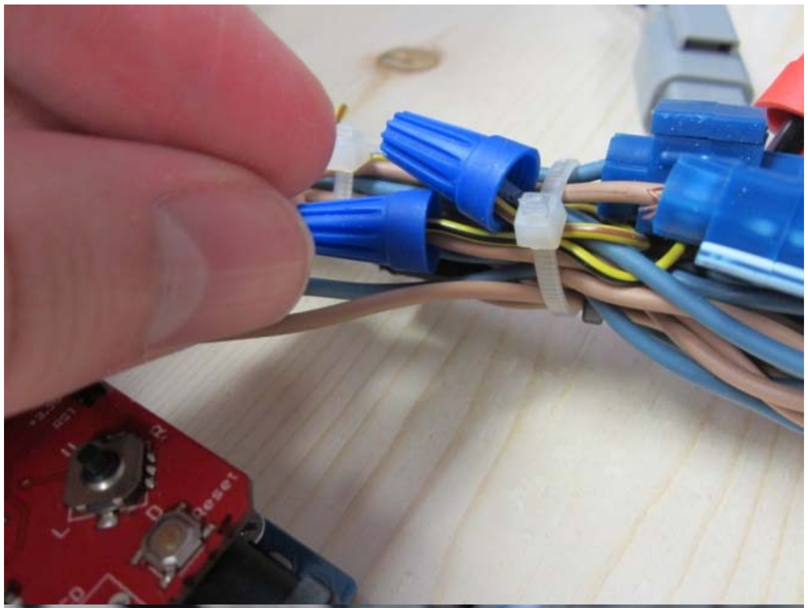
- Wire 1 BRN/BLK = Ground
- Wire 2 VIO/BLK = 12V power source(HOT IN ACCY, RUN AND START
- Wire 3 BLK/VIO = 12V power source(HOT IN START)
- Wire 15 RED/YEL = 12V power source(HOT AT ALL TIMES)
- Wire 16 GRN/BLU = 12V power source(HOT IN ON OR START)

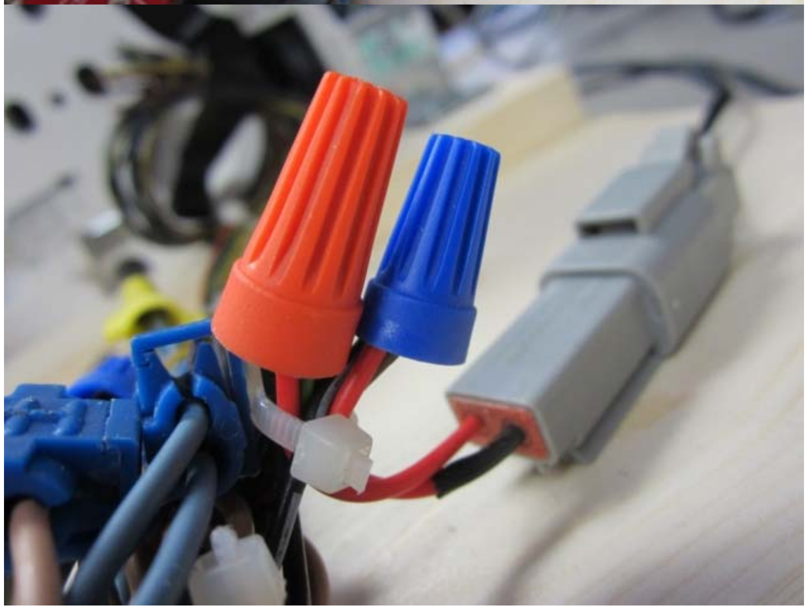
CAN data lines

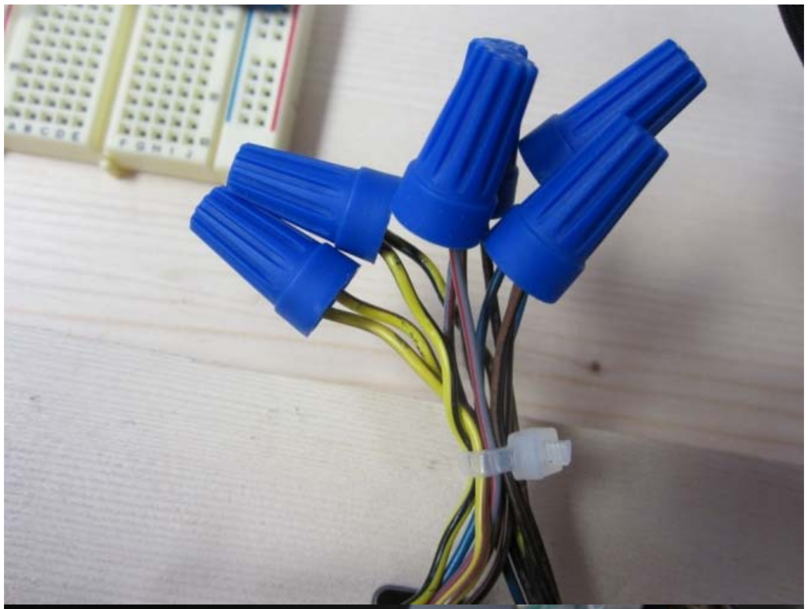
- Wire 13 YEL/BRN = CAN-L
- Wire 26 YEL/BLK = CAN-H

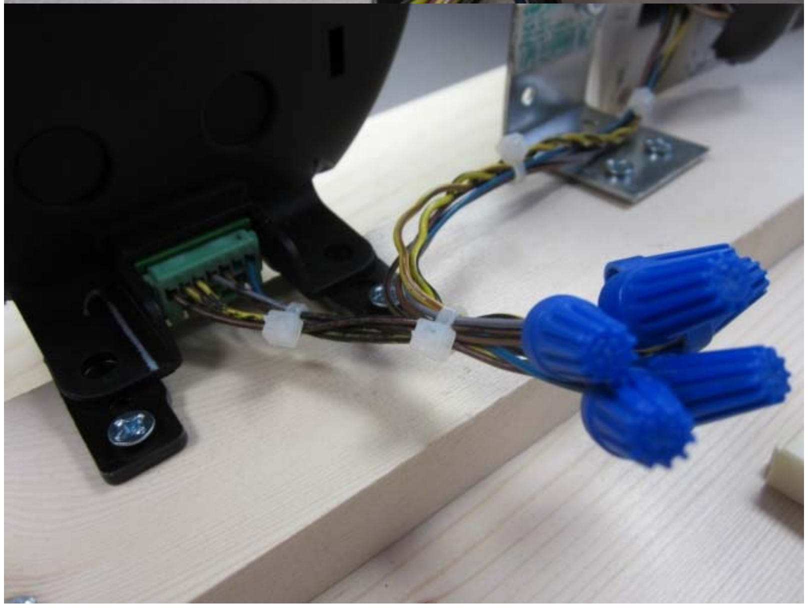
Once these wires were individually identified, we striped the wires, spliced, and soldered them together accordingly. We striped the ends off of the 12V DC power source and tied wires 2, 3, 15, and 16 of the instrument cluster unit to the positive lead of our power source (See images below). We also tied Wire 1 (ground) to the negative lead on our power supply. Next we connected the CAN high and low data lines to the network. We splice wires

13 and 26 from our instrument cluster into the CAN bus. Notice in the images below, CAN low is the blue wire of the CAN bus, and CAN high is the tan. After capping our wire leads to both power source and splicing CAN node entry points, we can plug in the power source to test that the instrument cluster powers on and works properly. If all goes correctly, a chime can be heard as soon as power is applied.

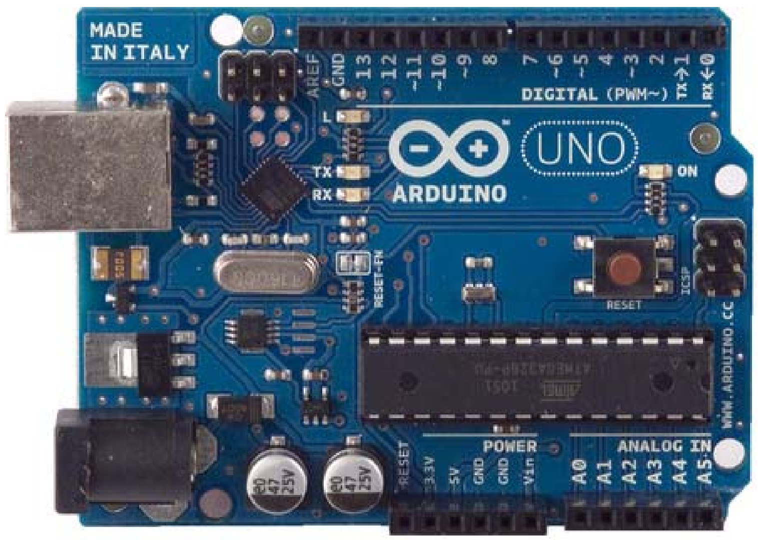




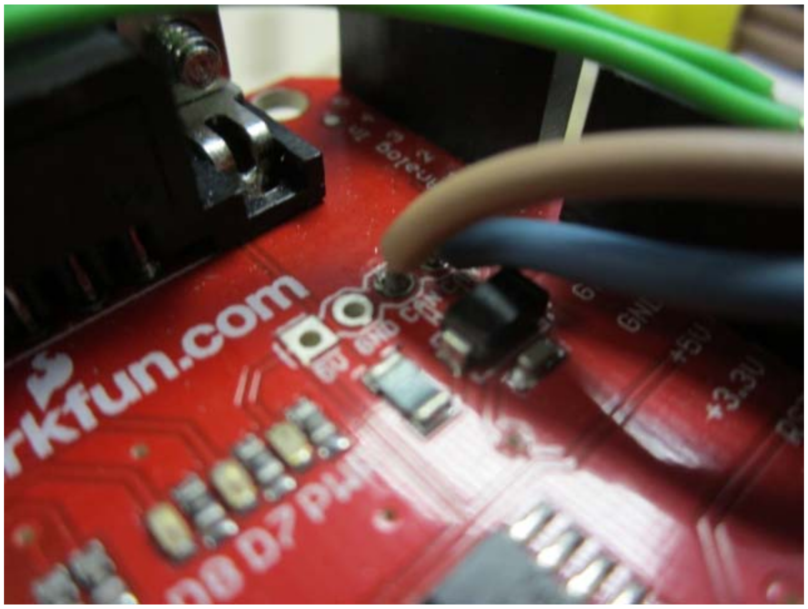


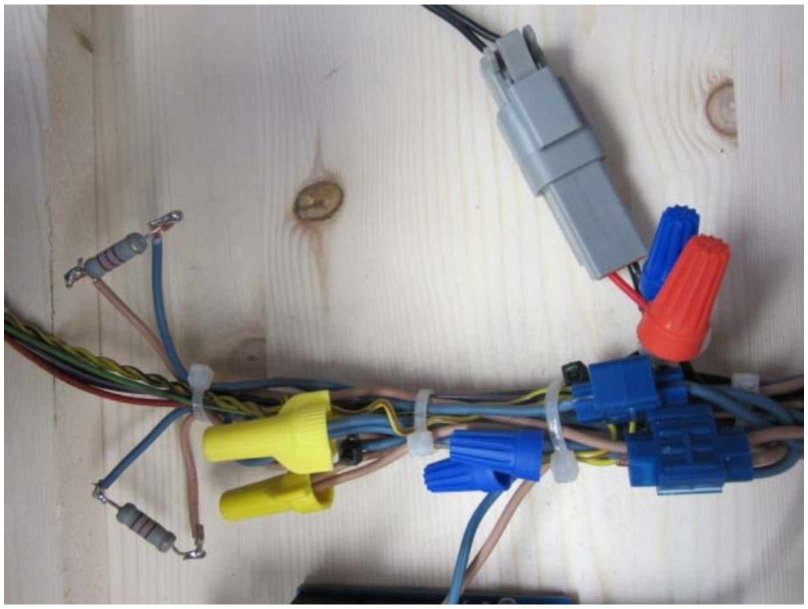


Now that the instrument cluster has successfully been connected to the CAN bus, we can configure the node that will be responsible for transmitting data to the instrument cluster unit. This node will be acting as a rogue device that an attacker could use to interact with other components on the CAN bus in nefarious ways. We will be using an Arduino Uno Rev 3 and a CAN-Shield to achieve this.

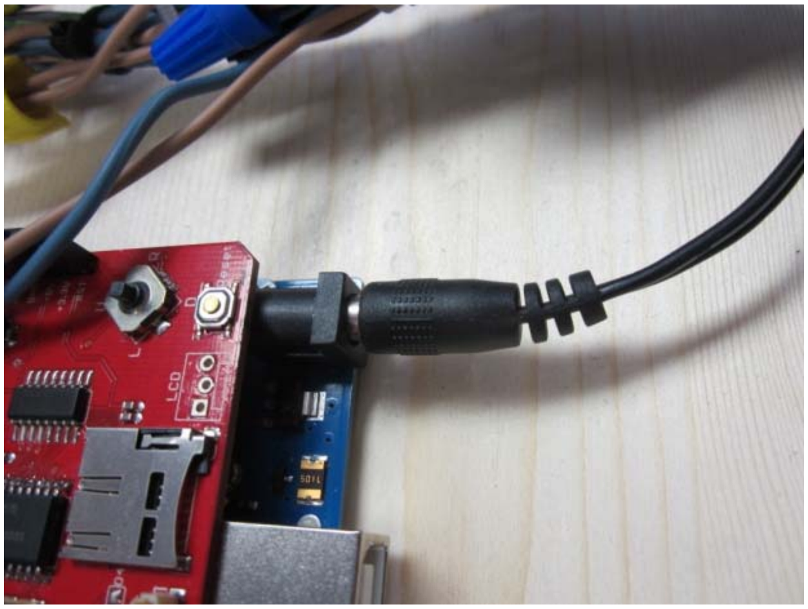


To interface the CAN shield with the data bus, we splice the 18 gauge twisted pair wire from the CAN bus and solder CAN-H and CAN-L wires coming into the pins on the CAN shield.

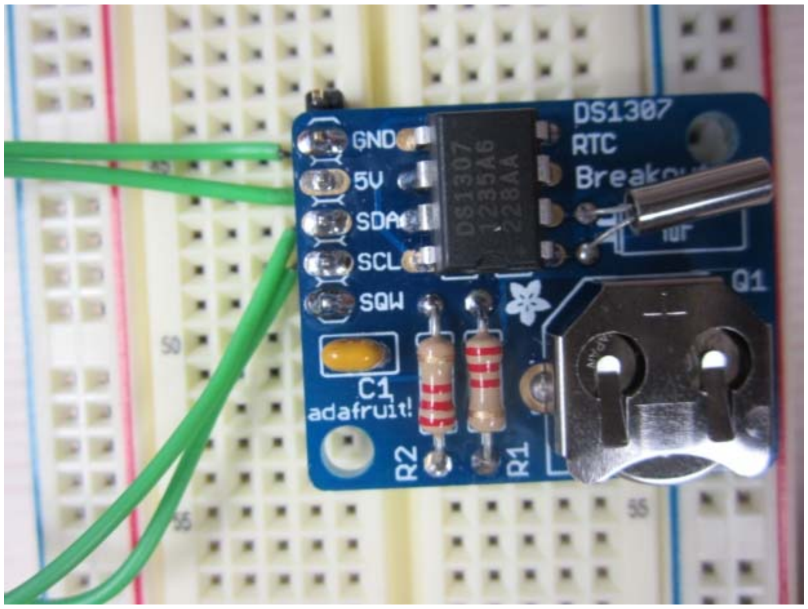


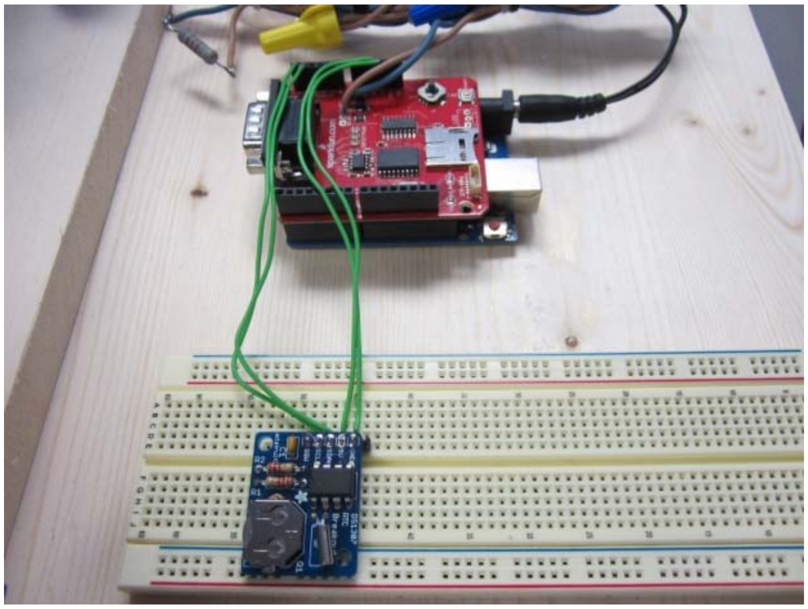


The Arduino will be powered from the same 12V DC power source that powers the instrument cluster. The Arduino Uno features a built in voltage regulator at the power port. Considering the safety benefit of the voltage regulator, applying 12V of power to the Arduino was not an issue as the Arduino Uno specifications explicitly state that the microcontroller can handle a recommended 7 - 12 volts.



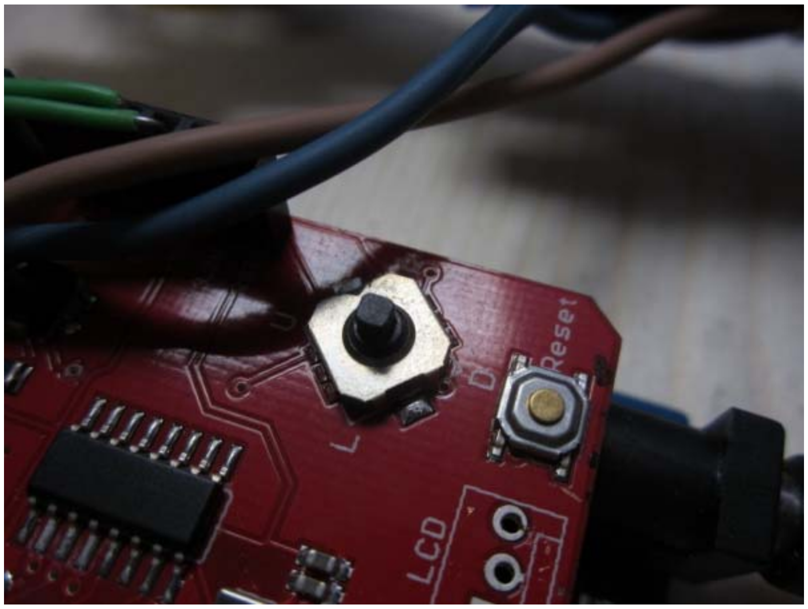
In order for the Arduino to keep track of accurate time, even when the power is disrupted, we will use a real time clock module (RTC). The RTC chip is powered with a small battery in order to retain the current time in the event of power loss. The Arduino will poll the time from the RTC in order to transmit the accurate time to the instrument cluster gauges. For demonstration purposes, we placed the RTC on a bread board separate from the Arduino.

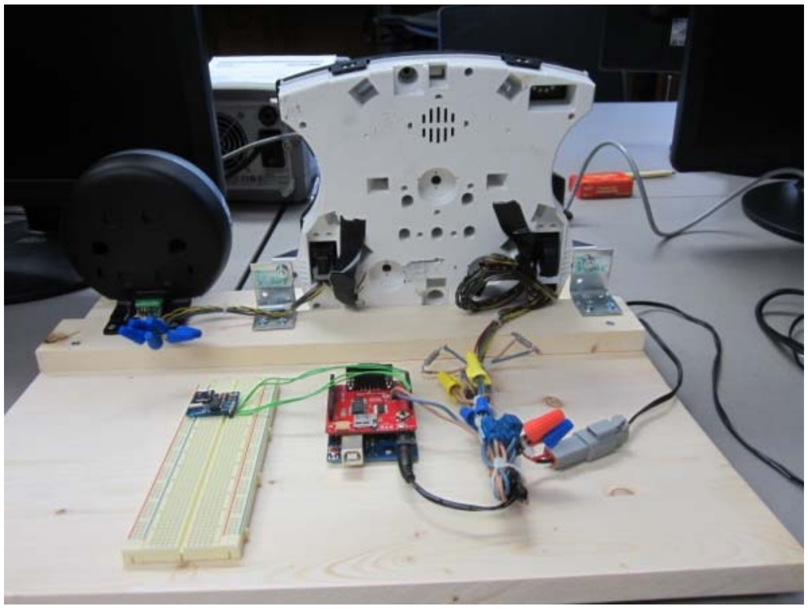


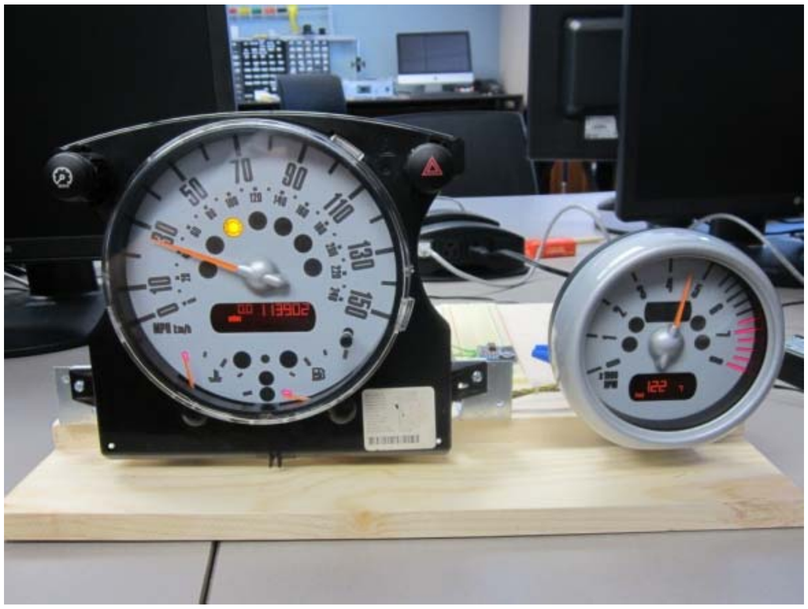


Everything up to this point should be connected, and all that should be left is to program the microcontroller. Other than the standard Arduino libraries, we will primarily be using the MCP2515 library to communicate with the CAN controller, and SPI library to communicate with the CAN shield using the serial peripheral interface. The MCP2515 library allows us to construct our own CAN Frame objects that can be injected onto the CAN bus. We will also be using the Wire.h and RTClib.h libraries to communicate with the RTC module.

For purposes of demonstration, the microcontroller was configured to work in two modes of operation that can easily be toggled by using the joystick click button on the CAN-Shield; Clock Mode, and Demo Mode (See images below). Clock mode obviously polls the time from the RTC to display the current time on the instrument cluster gauges via the CAN bus, and demo mode is used to increment the needles on the gauges arbitrarily to demonstrate the dynamic manipulation of CAN traffic. The final product (CAN Clock) is shown below showing a time of 2:47 p.m.


Reset
L
D
LCD





Code

Developed using the Arduino Programming Language which is based primarily on the C programming language.

```
/*
/*
Jason Staggs 3/11/2013
University of Tulsa
Crash Reconstruction Research Consortium (TU-CRRC)
http://tucrrc.utulsa.edu/canclock
CAN Clock Project
2003 Mini Cooper S
*/

//importing CAN shield library
#include <MCP2515.h>
#include <MCP2515_defs.h>
//Serial Perhiphial Interface
#include <SPI.h>
//RTC module library
#include <Wire.h>
#include "RTClib.h"


//Global variables
#define CLICK A4
//This defines the Slave Select pin for the CAN chip
#define CAN_CS 10
//interupt pin..
#define CAN_INT 2

MCP2515 CAN(CAN_CS,CAN_INT);

//Speedometer Frame object
Frame speedTx;
//Tachometer Frame object
Frame tachTx;


// CLOCK VARIABLES:
double hours = 0;
int minutes = 0;
int seconds = 0;

//clock boolean
boolean clock = true;

RTC_DS1307 RTC;

void setup()
{
  pinMode(A3, OUTPUT);
  digitalWrite(A3, HIGH);

  pinMode(A2, OUTPUT);
  digitalWrite(A2, LOW);

  Serial.begin(57600);
  Wire.begin();
  RTC.begin();

  if(! RTC.isrunning())
  {
   Serial.println("RTC is NOT running!");
  }


 SPI.setClockDivider(SPI_CLOCK_DIV2);
 SPI.setDataMode(SPI_MODE0);
 SPI.setBitOrder(MSBFIRST);
 SPI.begin();
 int baudRate=CAN.Init(500,16);
  if(baudRate>0) {
    Serial.println("MCP2515 Init OK ...");
    Serial.print("Baud Rate (kbps): ");
    Serial.println(baudRate,DEC);
  } else {
    Serial.println("MCP2515 Init Failed ...");
  }
  Serial.println("Initialization Complete.");

  //enable rollover...?
  CAN.BitModify(RXB0CTRL,0x04,0x04);

  pinMode(CLICK,INPUT);
  digitalWrite(CLICK, HIGH);

}

void loop()
{
  //runTest();
  if(clock)
  {
    clockMode();
  }

  if(digitalRead(CLICK) == 0 || clock == false)
  {
    clock = false;
    demoMode();
  }

  if(clock == false && digitalRead(CLICK) == 0)
 {
  clock = true;
 }
}

void clockMode()
{
  DateTime now = RTC.now();
  hours = now.hour();
  minutes = now.minute();
  seconds = now.second();

  if(hours > 12)
  {
   hours = hours - 12;
  }
  if(hours == 0)
  {
   hours = 12;
  }


  //fun action for hours
  if(minutes == 00 && seconds < 3)
  {
   hours = 15;
  }
  //Scale from program value to dial value
  hours = (hours + ((double)minutes / 60)) * 7.9;

    //fun action for minutes
    //scale minutes
  if(seconds < 3)
  {
    minutes = 80;
  }
  minutes = minutes *2.5;


  speedTx.id = 0x153;
  speedTx.srr = 0x0;
  speedTx.rtr = 0x0;
  speedTx.dlc = 0x8;
  speedTx.data[2] = hours;
  //Sending the frame on its way
  CAN.LoadBuffer(TXB0,speedTx);
  CAN.SendBuffer(TXB0);
  delay(5);

  tachTx.id = 0x316;
  tachTx.srr = 0x0;
  tachTx.rtr = 0x0;
  tachTx.dlc = 0x8;
  tachTx.data[3] = minutes;

  //Sending the frame on its way
  CAN.LoadBuffer(TXB0,tachTx);
  CAN.SendBuffer(TXB0);
  delay(80);


}

void demoMode()
{
 speedTx.id = 0x153;
  speedTx.srr = 0x0;
  speedTx.rtr = 0x0;
  speedTx.dlc = 0x8;
  speedTx.data[2] = hours;
  //Sending the frame on its way
  CAN.LoadBuffer(TXB0,speedTx);
  CAN.SendBuffer(TXB0);
  hours++;
  if(hours > 95)
  {
    hours = 0;
  }

  delay(5);

  tachTx.id = 0x316;
  tachTx.srr = 0x0;
  tachTx.rtr = 0x0;
  tachTx.dlc = 0x8;
  tachTx.data[3] = minutes;

  //Sending the frame on its way
  CAN.LoadBuffer(TXB0,tachTx);
  CAN.SendBuffer(TXB0);
  minutes++;
  delay(5);

  if(minutes > 150)
  {
    minutes = 0;
  }
  delay(80);
}
```

Resources

- **ProDemand (Mitchell Repair Information Company):** https://www.prodemand.com/
- **Arduino API documentation:** http://arduino.cc/en/Reference/HomePage/
- **Python API documentation:** http://www.python.org/doc/
- **Good introductory book to CAN:** http://www.amazon.com/Comprehensible-Guide-Controller-Area-Network/dp/0976511606/ref=sr_1_2?ie=UTF8&qid=1362956577&sr=8-2&keywords=CAN+bus
- **Easy to read/comprehend intro to the CAN standard:** http://www.ti.com/lit/an/sloa101a/sloa101a.pdf
- **GNU Plot:** http://www.gnuplot.info/

Retrieved from "http://wiki.tucrrc.utulsa.edu/index.php?title=Jason_Staggs_-_CAN_Clock&oldid=2937"