

# **Toyota's ETCS-i System and Latch-up as a Cause of SUA**

**Presentation to the  
National Academy of Sciences Committee  
on Electronic Vehicle Controls and  
Unintended Acceleration**

**by**

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24 January 2011**

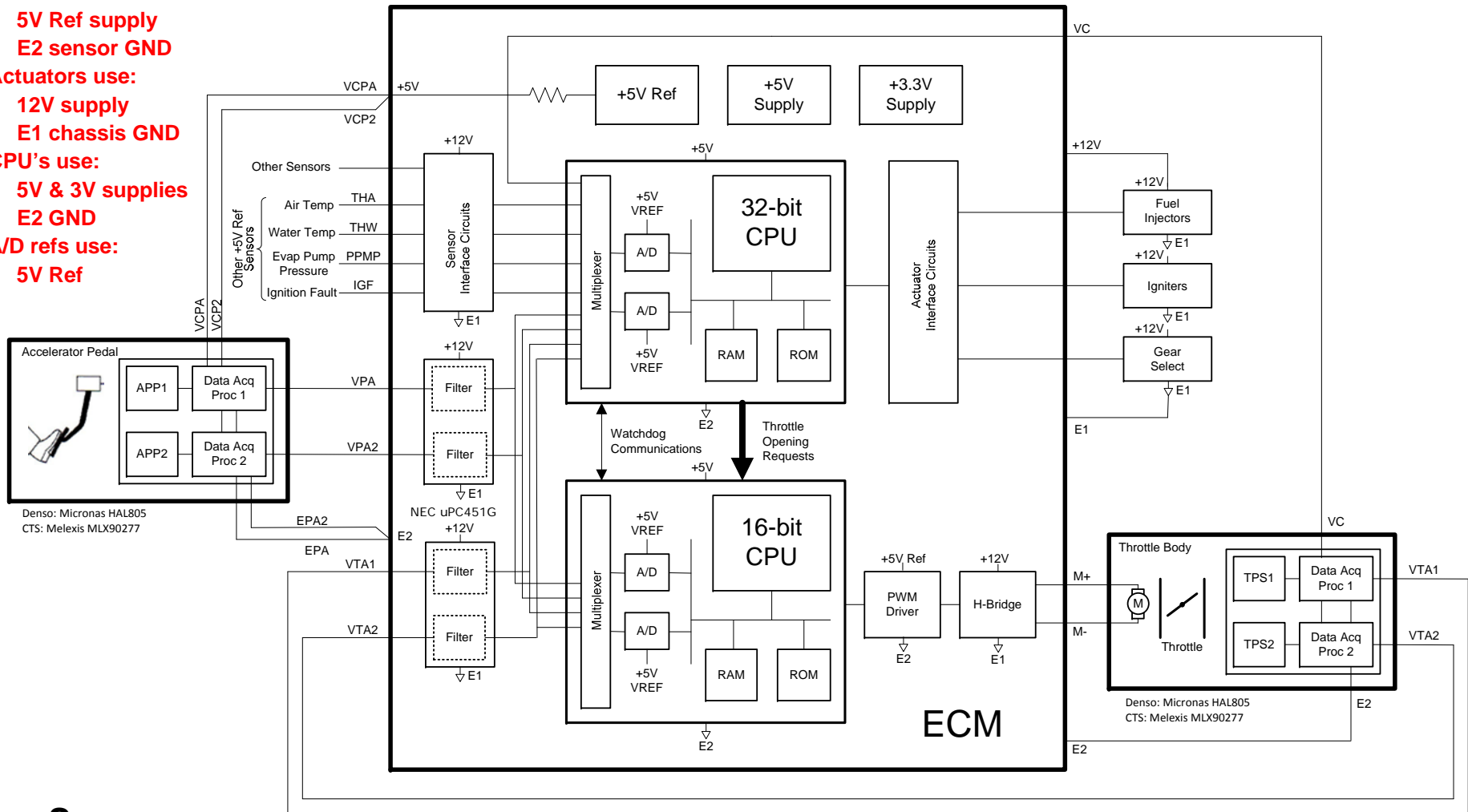
# Overview

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- **ETCS-i diagram**
- **APP and TPS sensors**
- **APP interface circuits**
  - Types of circuits
  - Possible faults
  - Power sequencing
- **Throttle motor interface circuits**
  - Types of circuits
  - Possible faults
- **Consequences of latch-up as a cause of SUA**
- **Where do we go from here?**

# Toyota's ETCS-i Electronic Throttle System

- Sensors use:
  - 5V Ref supply
  - E2 sensor GND
- Actuators use:
  - 12V supply
  - E1 chassis GND
- CPU's use:
  - 5V & 3V supplies
  - E2 GND
- A/D refs use:
  - 5V Ref



## Sources:

Toyota training manuals  
Exponent reports

Toyota & Denso Patents  
Part supplier specs & app notes

Papers  
TSB's

ECU observations (others)  
Engineering experience

# Toyota APP Sensors

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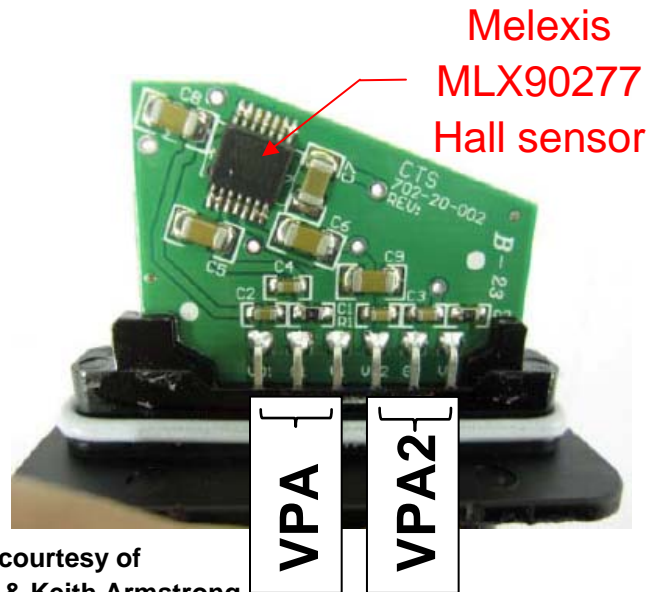
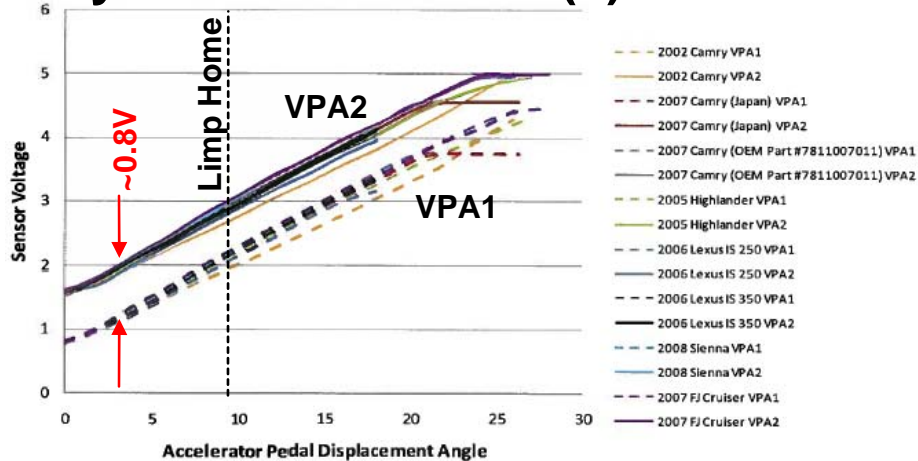


Photo courtesy of  
David Gilbert & Keith Armstrong

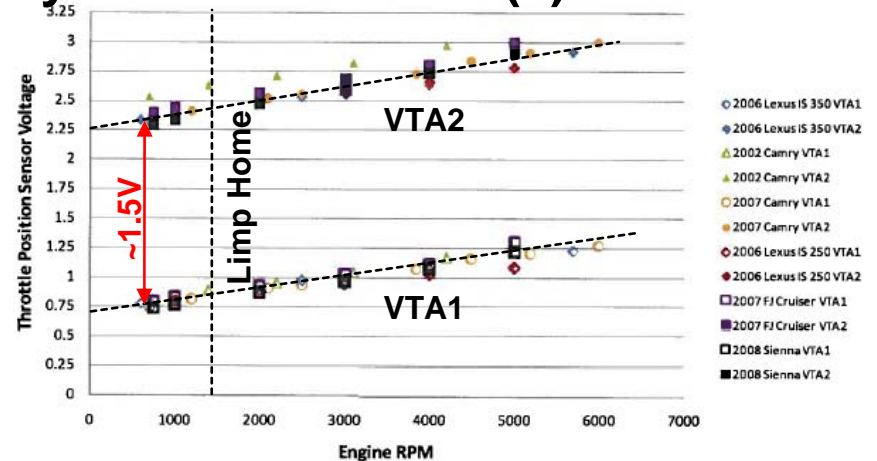
Two *identical* Hall-effect sensors in *one* package with *one common 5V supply voltage*.

# APP and TPS Sensors

## Toyota APP sensors (2)



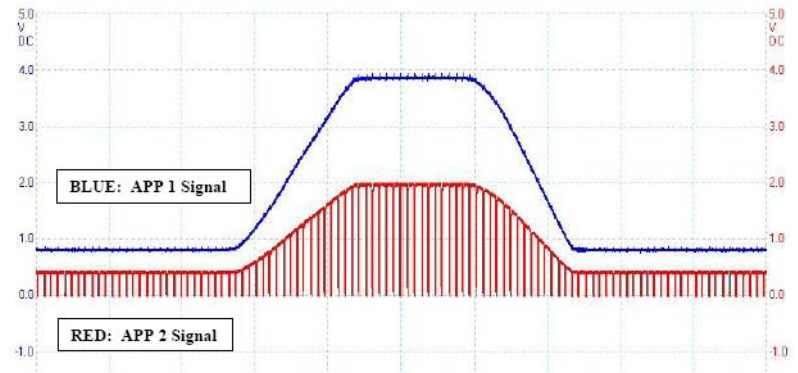
## Toyota TPS sensors (2)



## Ford APP sensors (3)



## GM APP sensors (2)

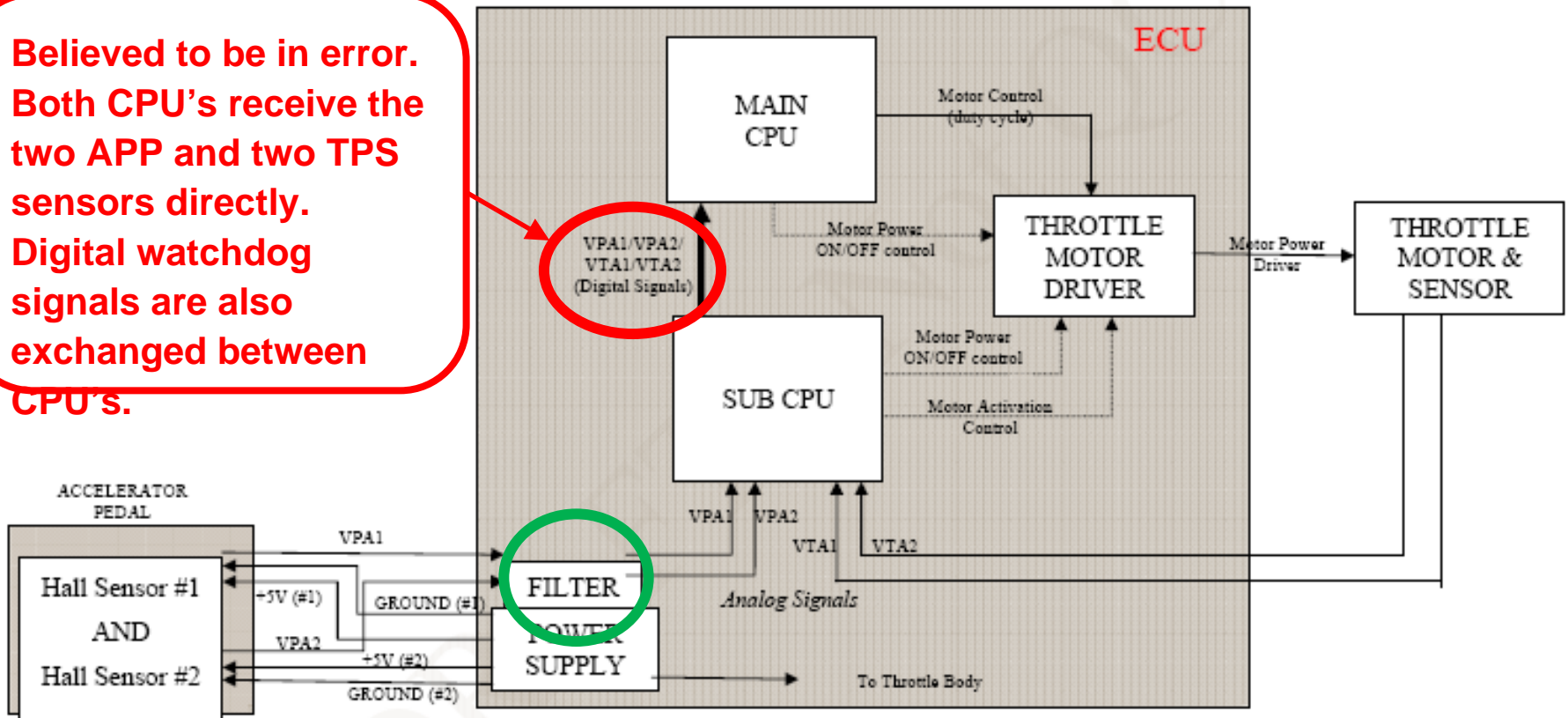


The APP2 signal is periodically pulled to ground to check for opens and shorts.

GM also uses different 5V supplies for each sensor

# Toyota ETCS-I System from Exponent Report

Believed to be in error. Both CPU's receive the two APP and two TPS sensors directly. Digital watchdog signals are also exchanged between CPU's.



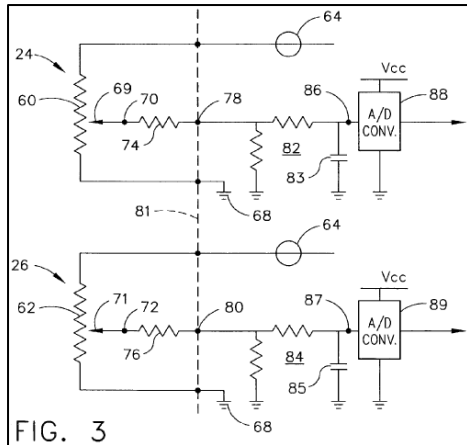
APP sensor low-pass filter used for:

- 1) filtering out cable noise
- 2) an anti-aliasing filter

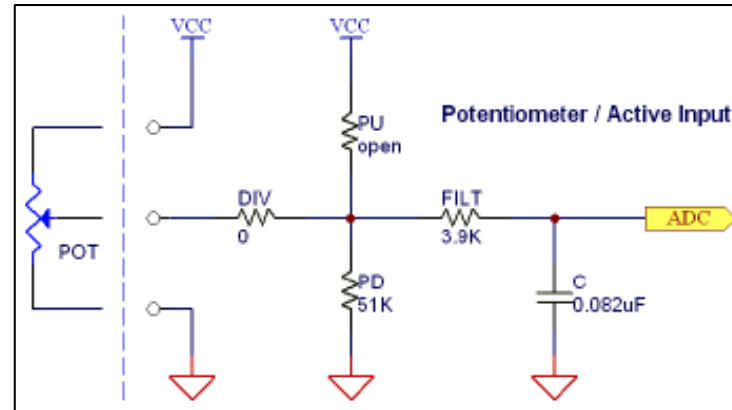
# APP Sensor Interface Circuits

## Passive Filters

GM Patent

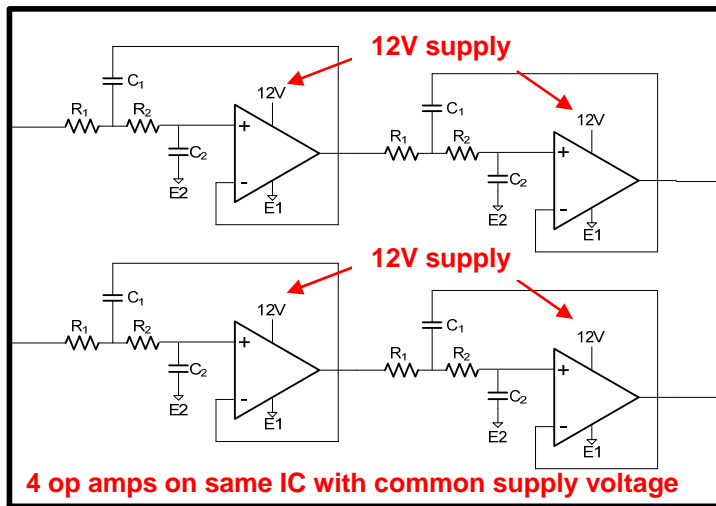


Driven Inc



## Active Filters

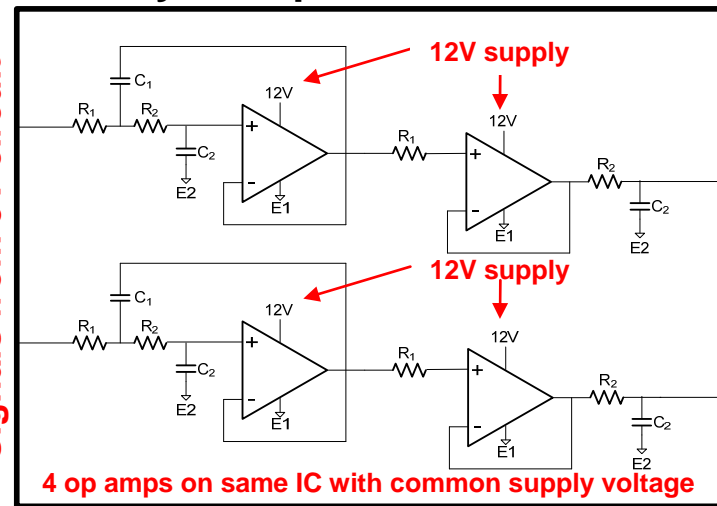
Toyota 2-Pole Filter



Signals from 5V circuit

Signals to 5V circuit

Toyota 1-pole Filter + Driver



Signals from 5V circuit

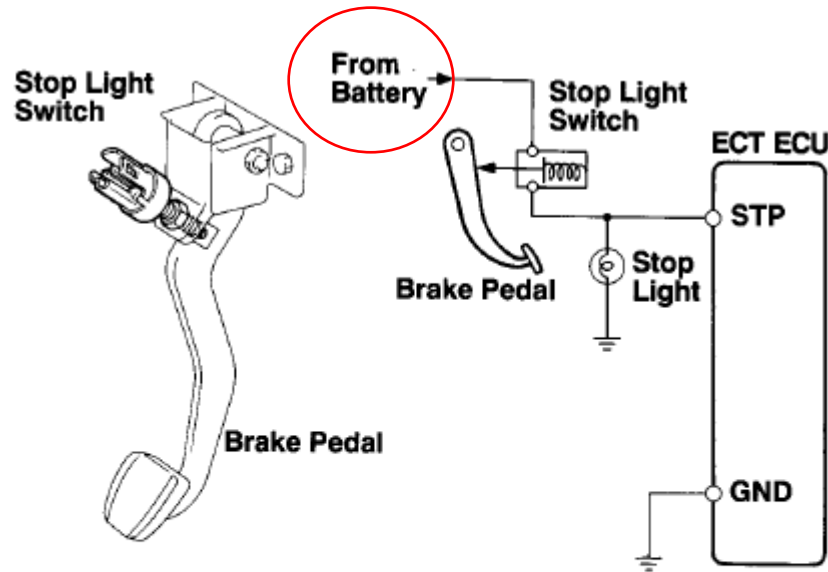
Signals to 5V circuit

# Possible Faults in Sensor I/O Circuits

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- **Loss of ground connection can lead to high output**
  - Open in ground wire inside harness or loom
  - Open in a solder joint connection to ground
- **Transients on 12V power rail can lead to latch-up**
  - The 12V power rail is loaded with transients
  - Negative transients can lead to transient latch-up
  - Large positive transients can lead to avalanche-induced latch-up
- **Transients on E1 ground rail can lead to latch-up**
- **Improper power sequencing can lead to latch-up**
  - **Input signals can not exceed the power rail at any time**
- **DC offset of E1 and E2 grounds can lead to op amp phase inversion**
  - **One driver noted that stomping on the accelerator stopped SUA**

# Potential Power Sequencing Issue



- 12V likely reduced to  $\leq 5V$  using a resistor voltage divider in ECU
- High S/N so filter not needed.

Brake Pedal	STP Terminal Voltage
Depressed	12 V
Released	0 V

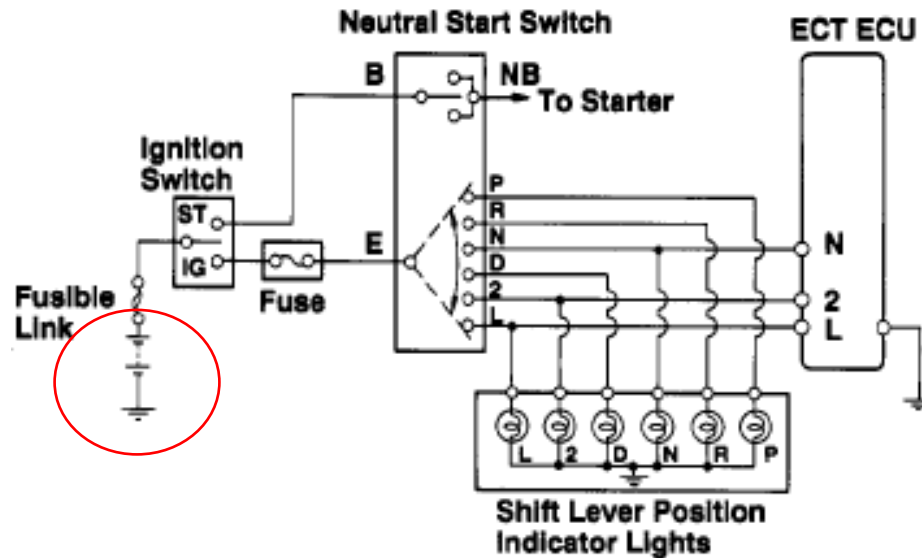
If the driver depresses the brake pedal before turning on the ignition, then a voltage is instantaneously applied at an input of both microcontrollers before their 5V power supplies turn on. This can cause latch-up of the microcontroller input circuits.

Also happens with 5V supply dropout and restart.

# Potential Power Sequencing Issue

## Neutral Start Switch

ECU monitors gear position through the neutral start switch.



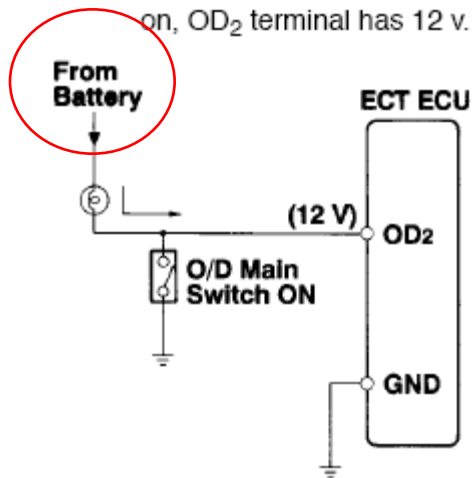
If the shift selector applies a 12V battery signal to the ECU when in PARK, then when the ignition switch is turned on, there will be a race condition between the 12V battery signal arriving at the microcontroller input and the regulated 5V rail turning on the  $\mu\text{C}$ .

Also happens with 5V supply dropout and restart.

# Other Potential Power Sequencing Issues

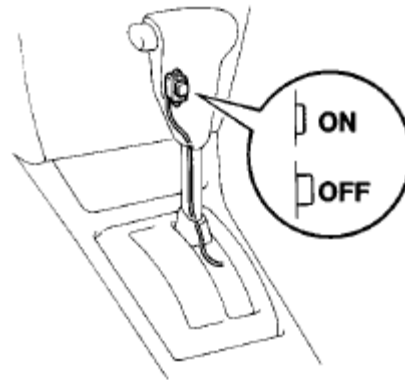
## Overdrive (O/D) Main Switch—ON

When O/D main switch is on, OD<sub>2</sub> terminal has 12 v.



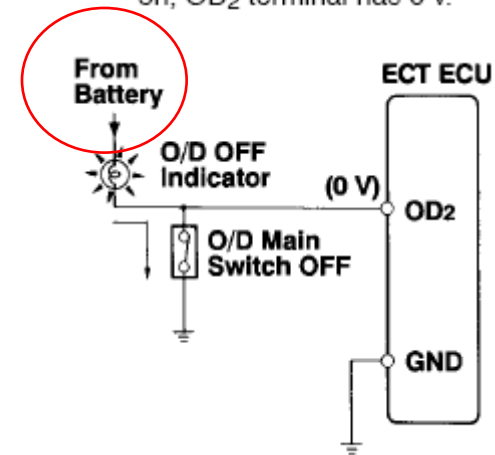
## Overdrive Main Switch

Allows driver to manually control overdrive.

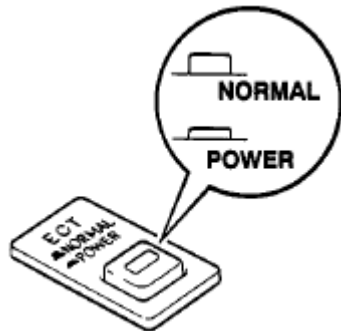


## Overdrive (O/D) Main Switch—OFF

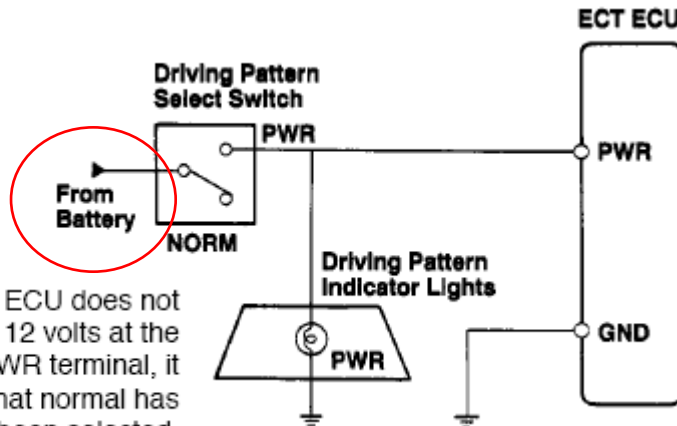
When O/D main switch is on, OD<sub>2</sub> terminal has 0 v.



## Drive Pattern Select Switch

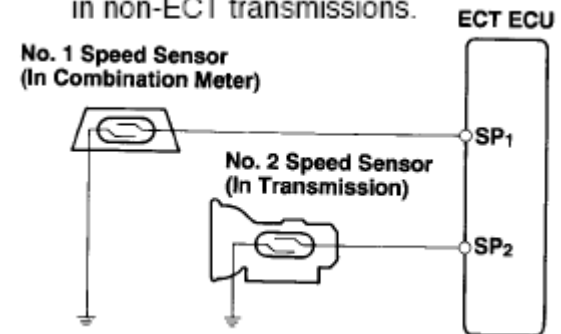


When the ECU does not receive 12 volts at the PWR terminal, it determines that normal has been selected.

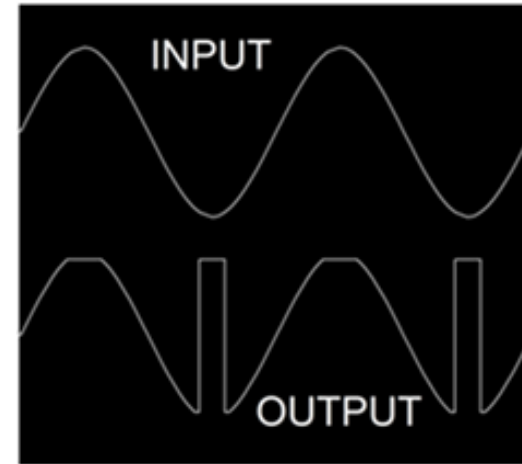
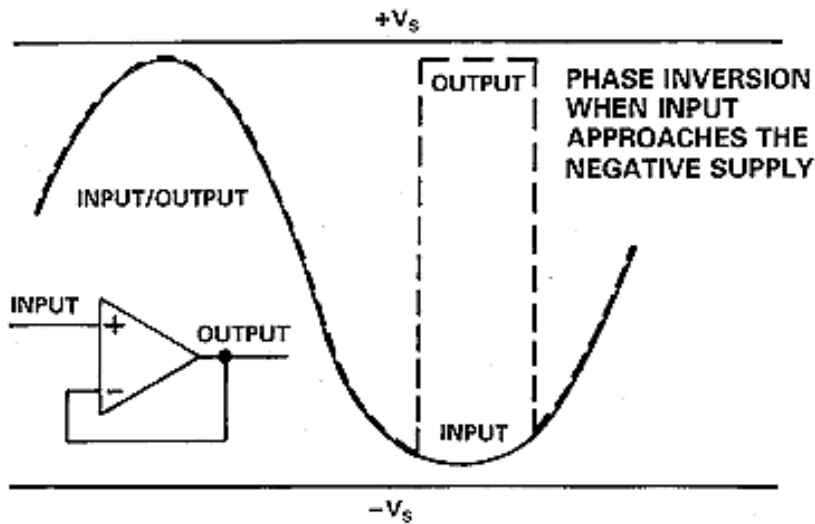


## Speed Sensors

Speed sensors are used in place of the governor valve in non-ECT transmissions.



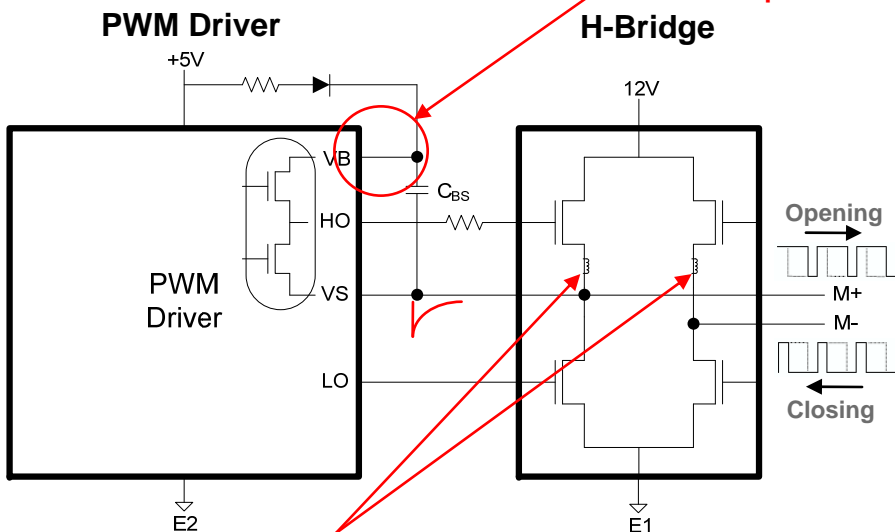
# Phase Inversion



- When an op amp input gets too close to the power rail, the output may switch to the opposite rail
- Occurs in JFET and bipolar op amps, but not CMOS
- Occurs more often when the op amp is used as a unity gain amplifier

# Throttle Motor Interface Circuitry

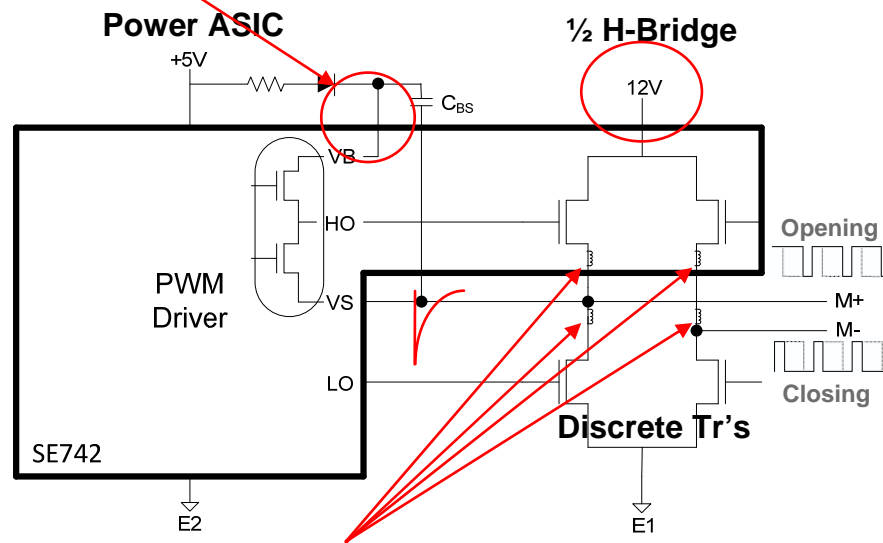
**Conventional Throttle Motor Interface Circuitry**



This node can exceed the avalanche breakdown voltage if  $C_{BS}$  is too small, causing latch-up.

Inductance  $L$  here can cause a negative  $Ldi/dt$  pulse on the  $VS$  node each time the high side transistors turn off, pulling  $VS$  below  $E1$  ground momentarily.

**Toyota Throttle Motor Interface Circuitry (2007 Camry)**



Partitioning the H-bridge increases the inductance  $L$ , increasing the magnitude of the negative  $Ldi/dt$  pulse on the  $VS$  node and increasing its likelihood of latch-up.

If the negative  $Ldi/dt$  pulse at  $VS$  exceeds the reverse bias on the substrate isolation junction inside the PWM driver IC, then latch-up occurs.

Acceptable operation is a delicate balance between  $-VS$  transient amplitude and PWM driver susceptibility

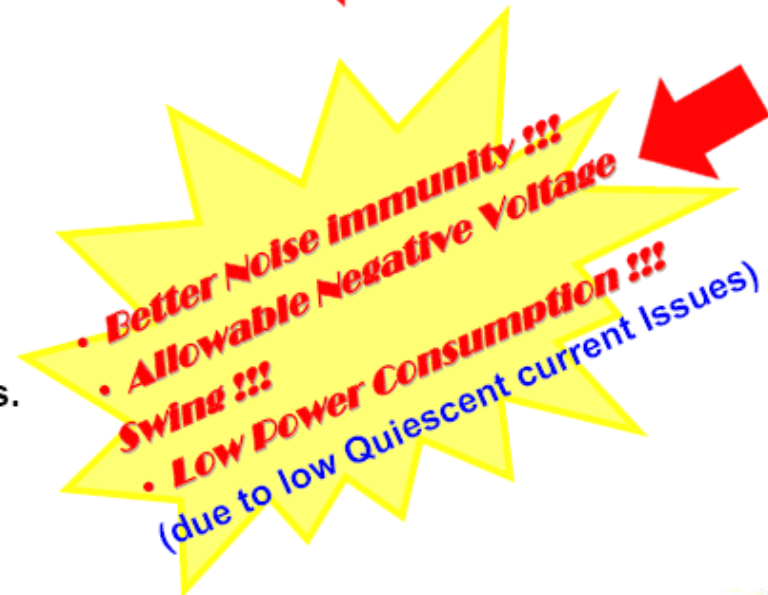
# PWM Latch-up Susceptibility Varies with Mfgr & Time



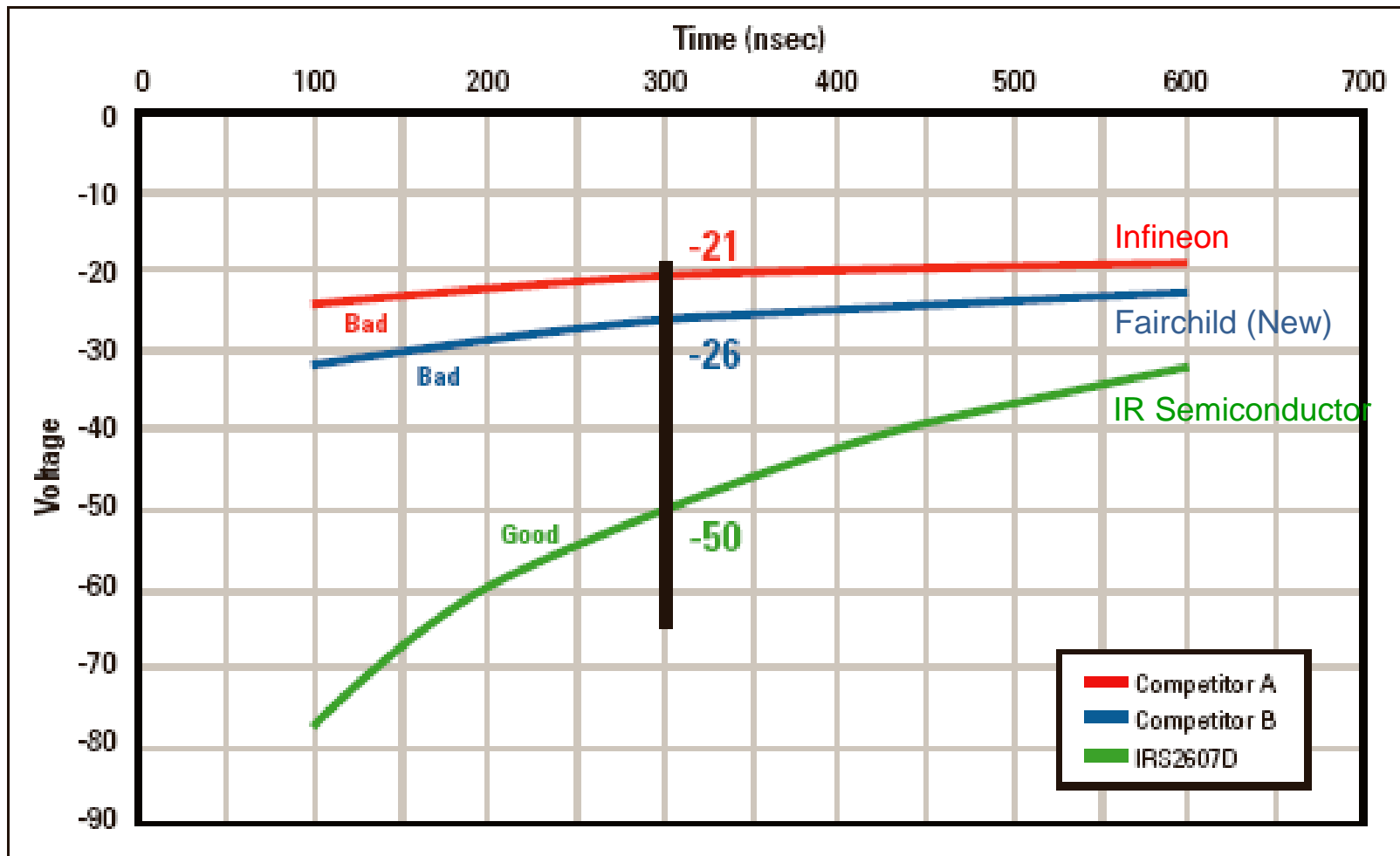
## Fairchild HVIC Advantages



- Better noise immunity.  
(Owing to noise canceling circuit over high dv/dt common-mode noise)
- Extended allowable negative voltage: -9.8V at  $V_{BIAS} = 15V$
- Low power consumption.  
(Owing to low quiescent current issues:  
 $I_{qbs}/qcc$  is lower than other competitors)
- UVLO function for both channels.
- Matched propagation delay below 50nsec.
- Floating channel designed  
for bootstrap operation to +600V.
- TTL compatible input logic threshold levels.



# PWM Latch-up Susceptibility Varies with Mfgr & Time



**Latch-up occurs if negative VS transient exceeds manufacturer's substrate junction reverse bias voltage (i.e., below each curve)**

# Possible Faults in PWM Driver Circuit

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- **Negative transient at VS reference pin can forward bias substrate isolation junction and cause latch-up**
  - VS goes below E1 ground temporarily when top transistor turns off due to inductance between transistors
  - Happens in all circuits with bootstrap capacitor
  - PWM drivers vary in ability to withstand negative transient
- **Positive transient on VB pin can exceed avalanche voltage and cause latch-up**
  - Smaller capacitance increases voltage
  - Capacitance decreases with age making older vehicles more susceptible
- **Negative transient on 5V rail (or 12V rail if present) can cause transient latch-up**
- **Glitches on PWM driver inputs can cause latch-up**

# Consequences of Latch-up as a Cause of SUA

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- Latch-up in APP sensor input circuits can be detected and mitigated by the ECU
- Latch-up in PWM driver circuit cannot be stopped by the ECU because the ECU is not in control of the throttle
  - **Implies smart brakes cannot eliminate sudden acceleration in this case**
  - The only way to stop sudden acceleration due to PWM driver latch-up is by shutting off the throttle motor current in the H-bridge
    - ◆ **By turning off the ignition**
    - ◆ **By detecting a runaway throttle condition and turning off the 12V supply current**
    - ◆ **By detecting a runaway throttle condition and turning off the H-bridge driver outputs (e.g., by using a Decelerator product)**

# Where Do We Go From Here?

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- **Need teardowns to validate circuit diagram**
- **Need fast scope observations of real circuit nodes and power supplies on vehicles**
  - **Preferably on vehicles that have experienced SUA**
  - **Voltmeters and ODB code readers are ineffective in observing transients**
- **Need to induce transients conductively into real circuits on vehicles**
  - **Different amplitudes, pulse widths, and timings**
  - **Proper vehicle operating conditions**
  - **Radiative EMI testing does not excite the same latch-up mechanisms as conductive EMI testing**
- **Require Toyota to supply circuit schematics and to explain how SUA occurs when faults they cite take place at the cited circuit node.**

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# Questions?

# CPU's Used by Toyota

Company	Vehicle	ECU Mfgr	32-bit Microcontroller	16-bit Microcontroller
Toyota	2006 Innova	Denso	Fujitsu TDFP11-0003 (76F0040)	
Toyota	<2004 Prius (Gen1/NHW11)	Denso	Fujitsu TDFP11-0003 (76F0040)	
Toyota	>2004 Prius (Gen2/NHW20)	Denso	NEC uPD70F3155 (V850ESFJ3)	Mitsubishi MC16-80 (M30800)
Toyota	Avalon	Denso	NEC uPD70F3155 (V850ESFJ3)	Mitsubishi MC16-80 (M30800)
Toyota	Corolla (USA) Matrix (USA)	Delphi <sup>3)</sup>	Freescale MPC565 (Spanish Oak)	Freescale HCS12 ( <a href="#">SC511507MZP56</a> )
Toyota	2011 Corolla	Denso <sup>4)</sup>	Renesas	Mitsubishi MC16-28 (M30800)
Ford	All Ford (Gen II) Lincoln Mercury		Freescale MPC555 (Black Oak) MPC565 (Spanish Oak)	Freescale HCS12 (E-Quizzer)
Chrysler	All		Freescale MPC5554 (Copperhead)	Freescale HCS12
GM	All	Delphi	Freescale MPC5554 (Copperhead)	Freescale HCS12
Buick	Park Avenue		Bosch E77	

1. NEC, Mitsubishi, and Hitachi are now Renesas Inc.
2. Freescale is a spinoff of Motorola Inc.
3. Prior to 2011 Delphi made the ECU for all USA-made Corolla and Matrix vehicles
4. Prior to 2011 Denso made the ECU for the Japanese-made Corolla and matrix vehicles.
5. Starting in 2011 Denso will make the ECU for all Corolla and Matrix vehicles

# More Thoughts

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Latch-up can explain:

- SUA may occur at any speed
- Clunking sound heard at start of SUA by hitting stop at max motor position
- Turning off ignition eliminates SUA
- Lack of OBD codes by crowbarring of 5V supply bringing down all sensors
- Re-occurrence is more likely after a vehicle experiences SUA

Only latch-up can explain the Haggerty (NJ) 2007 Avalon incident:

- No accelerator pedal sticking
- No floor mat interference
- High RPM continued when driver was outside the vehicle
- Eliminated by turning off ignition
- Multiple incidents (5) occurred in same vehicle

SUA and Corolla stalling can both be explained by the same mechanism

- SUA  $\Rightarrow$  PWM latch-up causes throttle motor to go to max open position
- Stalling  $\Rightarrow$  PWM latch-up causes throttle motor to go to max closed position
- Toyota ascribes stalling to cracks in PWB solder ball joint or a varistor
  - Not consistent with turning off ignition stopping stalling
  - If true, may also explain sudden acceleration

# More Thoughts Cont'd

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**A 2003 NASA X-43A/HXLV rocket malfunction was traced to latch-up in the PWM driver controlling the fin actuator motor**

- **NASA created a “Lessons Learned” document to prevent re-occurrence**

**Limp-home position:**

- **Prevents throttle from sticking in a closed position**
- **Achieved by two opposing springs**
- **Approximately 8° open provides 1500 RPM**
- **Vehicle acceleration  $\Rightarrow$  throttle opening increases  $>$  limp-home position**
- **Vehicle idling  $\Rightarrow$  throttle opening decreases  $<$  limp-home pos (~800 RPM)**
- **Limp-home position causes non-linearity in cruise control PID algorithm**

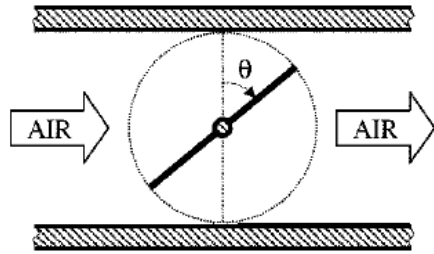
**Five people have had SUA occur in two different Toyota vehicles**

- **Implies driver is doing something to increase probability of SUA**

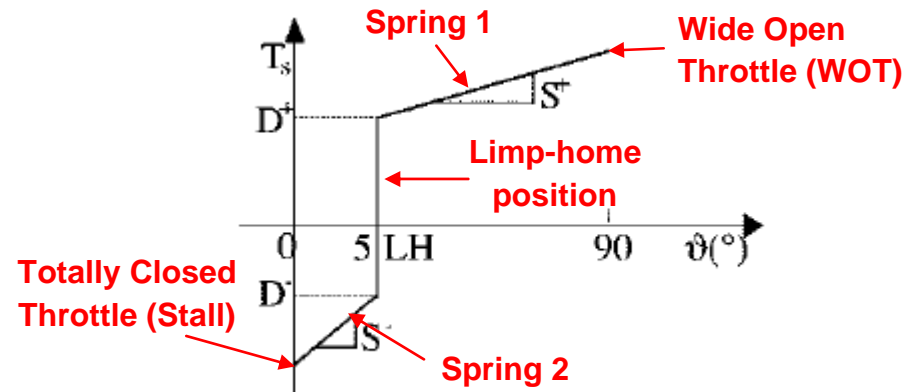
**Please don't limit discussion between NAS team and outside experts.**

**Instead, present results periodically and encourage dialog**

# Limp-Home Position



Throttle body functional scheme.



Safety spring torque ( $T_s$ ) as a function of throttle position ( $\vartheta$ ).

	Minimum value	Typical value	Maximum value
LH position [°]	3	–	15
$D^+$ , $D^-$ [Nm]	0.07	–	0.08
$S^+$ , $S^-$ [Nm/rad]	$13 \cdot 10^{-3}$	–	$45 \cdot 10^{-3}$

## Limp-home position:

- Prevents throttle from sticking in a closed position
- Achieved by two opposing springs
- Approximately 8° open provides 1500 RPM
- Vehicle acceleration  $\Rightarrow$  throttle opening increases  $>$  limp-home position
- Vehicle idling  $\Rightarrow$  throttle opening decreases  $<$  limp-home pos ( $\sim$ 800 RPM)
- Limp-home position causes non-linearity in cruise control PID algorithm

C. Rossi, A. Tilli, and A. Tonielli, “Robust Control of a Throttle Body for Drive by Wire Operation Of Automobile Engines”, IEEE Transactions on Control Systems Technology, Vol 8, No 6, November 2000., p993.

# NASA X-43A/HXLV Flight Control Mishap (2003)

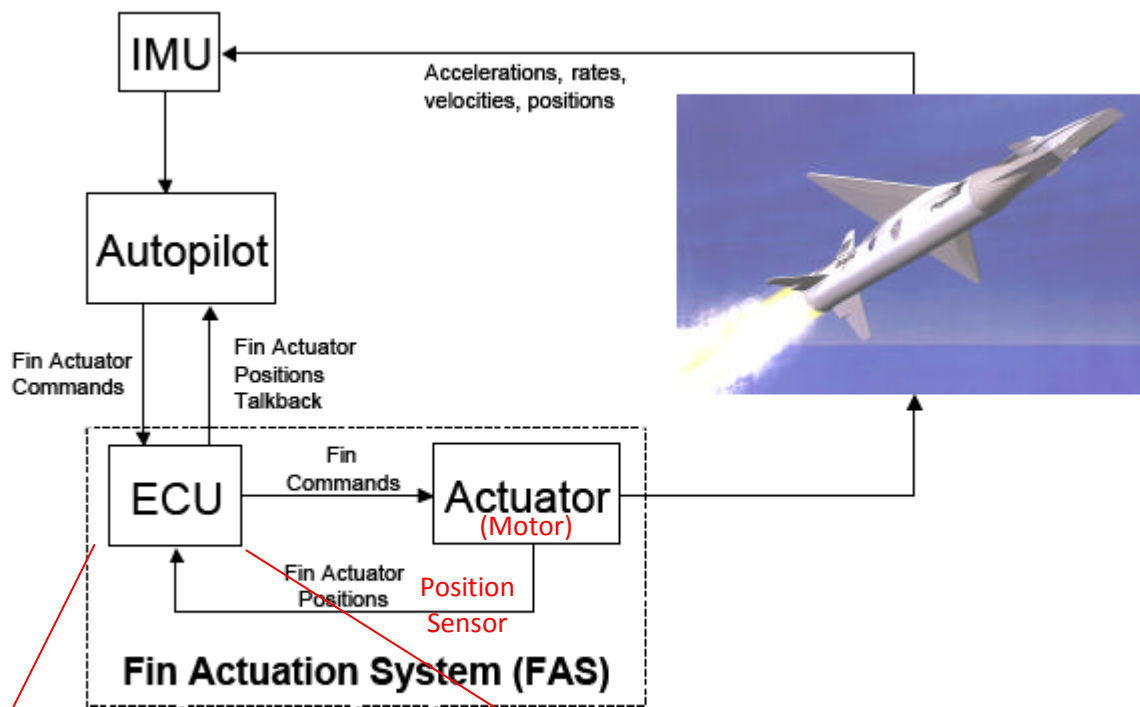
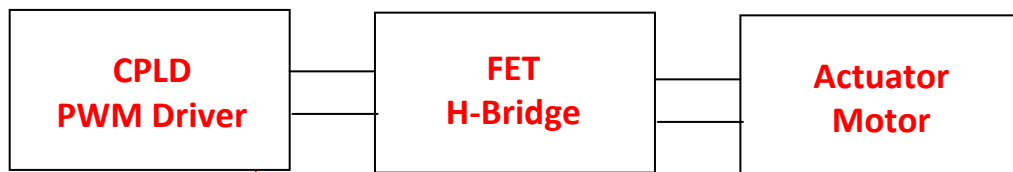


Figure 6-6. HXLV Control System Diagram



Latch-up  
Occurred  
in this IC

The first sign of a serious design problem with the FAS modifications came in early October 2003. An ECU failed during a cold-soak test simulating temperatures at high altitudes. The failures occurred when the actuators were commanded to slew at a high rate. Instead, the CPLD ceased processing, which is known as a “latch-up” condition. Should this occur in flight, the fins would stop moving, control would be lost, and the mission would fail. The unit was returned to the vendor for analysis. The contractor attempted to reproduce the failures with the ECU instrumented for diagnostic data. Although several cold-temperature cycles were made, each time the channel controlling the fin operated normally.<sup>32</sup> Griff Corpening, the Dryden chief engineer for the two X-43A Mach 7 flights, recalled that “as soon as you hooked up your diagnostic equipment, it wouldn’t [latch up] anymore. So the problem was so subtle that as soon as you interfered in any way with the circuitry, it wouldn’t [latch up].”<sup>33</sup> Not until January of 2004 was the problem resolved. The latch-up was triggered by excessive electronic noise in the ECU power boards during “current-limit states.” These occurred when the maximum electrical current value was being sent to the field effect transistors. Once the noise reached a certain level, it would cause the CPLDs to latch up.  
[http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070021686\\_2007019790.pdf](http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070021686_2007019790.pdf)

“It was found that a combination of noise, back-feeding through the outputs of a logic device, and ground bounce were able to produce sufficient voltage below the components’ manufacturer specified limit of -0.5 volts that resulted in the FET-based device “latch-up”. The outputs then went into a tri-state condition, allowing the output voltage to gradually rise to the rail voltage. This produced a destructive condition for the H-bridge output transistors. Also, the component manufacturer determined that once the logic device was exposed to this “latch-up” condition, it became more susceptible to future latch-ups.”

-- NASA Public Lessons Learned Entry: 1603

[http://www.nasa.gov/offices/oce/llis/delta\\_lesson\\_2006/hdm/1603.html](http://www.nasa.gov/offices/oce/llis/delta_lesson_2006/hdm/1603.html)