Tin whisker analysis of Toyota's electronic throttle controls

Bhanu Sood, Michael Osterman and Michael Pecht
Center for Advanced Life Cycle Engineering, University of Maryland, College Park, Maryland, USA

Abstract

Purpose – This paper aims to present the results of physical analysis that was conducted on Toyota's electronic engine control system including accelerator pedal position sensors (APPSs). The paper overviews the analyses and focuses on the discovery of tin whiskers found in the accelerator pedal assembly, which are an electrical failure concern.

Design/methodology/approach – Analytical techniques such as X-ray fluorescence spectroscopy, scanning electron microscopy and energy dispersive spectroscopy are utilized to present a construction analysis of the APPS.

Findings – The use of a tin finish in the APPS is a cause for concern. Tin finishes are known to produce metal whiskers that are conductive and capable of creating unintended current leakage paths. In the analysis, a significant number of tin whiskers were found.

Research limitations/implications – The methodology discussed in this paper can be implemented to inspect for tin whiskers in the APPSs.

Originality/value – The paper begins a construction analysis of different parts of the Toyota engine control module and APPSs and then moves on to highlight electronics design issues that can comprise the engine control system and cause unintended consequences.

Keywords Automotive industry, Electronic engine control system, Accelerator pedal position sensors, Tin whiskers, PCB, Electrical faults

Paper type Technical paper

Electronic throttle control system

Over the past 50 years, electronics have been replacing and adding functionality to the power and control systems in vehicles. For example, in today's cars, electronic engine control enables coordination of spark ignition, cruise control, air to fuel ratios, idle speed and complex variable valve timing. The electronics have the ability to provide high engine performance, reduce pollution and a reduced risk for engine damage. However, the replacement of mechanical systems by electronics introduces new risks in terms of reliability and safety.

Figure 1 shows a typical implementation of electronics associated with engine control. In this example, when the accelerator pedal is pressed, an accelerator pedal position sensor (APPS) provides a voltage output to the engine control module (ECM). This voltage output is proportional to the displacement of the pedal. Filters inside the control unit remove electronic "noise" from the APPS input signal. Based on the vehicle speed, the APPS signal and inputs from the idle speed control sensor, cruise control, transmission shift control and vehicle stability control, the ECM analyzes the intent of the driver, calculates the required engine torque and sets the required throttle plate angle. The ECM also monitors and acts upon signals from the cruise control and the brakes. The results are all communicated to other electronic subsystems through a control area network bus. If any of these subsystems or components fails to function properly, then there is an opportunity for improper functioning of the vehicle and thus safety risks. For example, in 1988, Toyota had two recalls associated with sudden acceleration of their vehicles due to faults in their cruise control subsystems (Correspondence between Toyota Motor Corporate Services, NHTSA and Others, 1990; Correspondence between Toyota Motor Corporate Services, NHTSA and Others, 1986). Kimseng *et al.* (1999) also found conditions where a failure of the cruise control could make a vehicle transition to wide open throttle.

In this study, an engine control system, including the ECM, an accelerator pedal unit, throttle body, electrical connectors and electrical connecting cables from a 2005 Toyota Camry, XLE, V-6 were examined. An accelerator pedal unit from a 2002 Camry was also examined. The ECM of the 2005 vehicle is shown in Figure 2. The ECM printed circuit board receives and outputs over 100 power, sensor and control circuits from and to other subsystems of the engine control system. The throttle body controls the air flowing into the engine compartment by varying the angle of a valve plate. When the throttle opens, the intake manifold receives more air. An airflow sensor mounted in the manifold and connected to the ECM, measures the changes in air flow into the manifold. When the ECU receives a signal from the airflow sensor that there is an increased amount of air, the ECU sends a signal to the fuel pump to increase the amount of fuel to the fuel injectors. This helps to maintain the proper air and fuel mixture. The valve plate angle of the electronic throttle control is controlled by the ECU, based on the signals received from the accelerator and a number of other sensors located in different parts on the automobile.

Accelerator pedal unit

The accelerator pedal unit (Figure 3) includes a foot pedal that is connected to a metal arm which pivots on an axle unit. The axle unit houses a restoring spring designed to provide resistance and restore the pedal to its at rest position in the absence of a load on the pedal. The APPS is a molded plastic

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Figure 1 Schematic representation of the engine throttle control

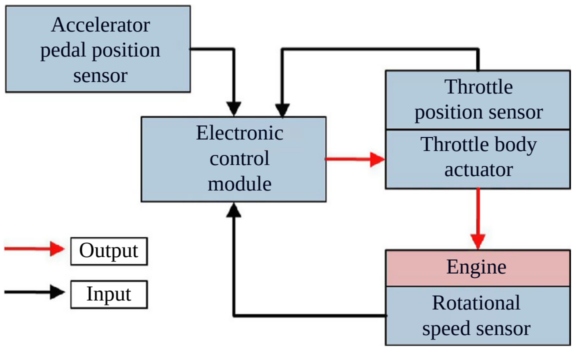
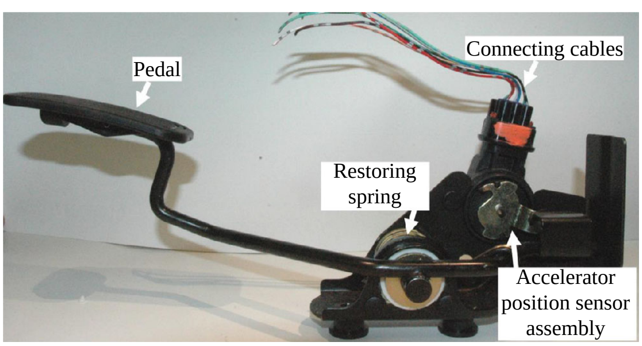


Figure 2 The engine control unit of a 2005 Toyota Camry after removal of top cover

Figure 3 Accelerator pedal unit of a 2005 Toyota Camry shown in idle position



structure with a six-pin connector and a spring-loaded rotating disk, which provides output voltages that are proportional to the position of the pedal based on a reference input voltage (Figure 4). These output voltages are monitored by the ECU, which controls engine power and acceleration (White and Zdanys, 1995).

To examine the behaviour of the APPS, electrical resistance between selected connector pins was monitored while incrementally moving the accelerator pedal from its idle position to its maximum depressed or full speed position in six steps, as shown in Figure 5. The resistance measurements between pins 2 and 4, as well as between pins 5 and 6, are shown in Figure 6.

Figure 7 shows the interior of the APPS, exposed by cutting away a portion of the plastic housing. The cavity contains

Figure 4 An acceleration pedal position sensor of a 2005 Toyota Camry removed from the accelerator pedal unit

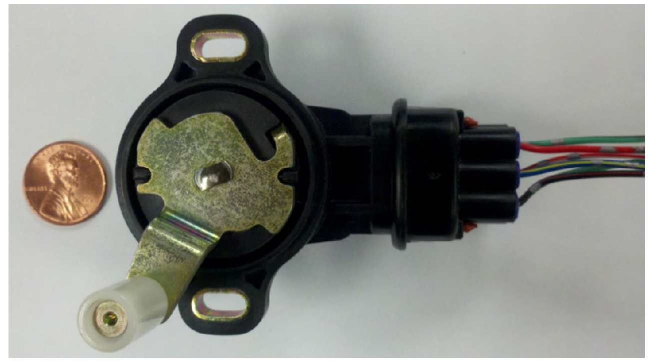


Figure 5 Accelerator pedal of the 2005 Toyota Camry can be moved between the idle position and full speed position

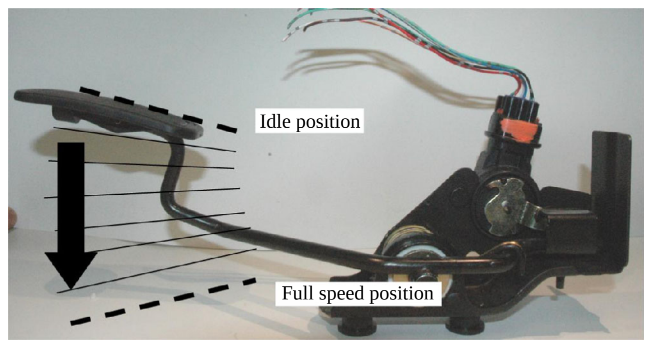
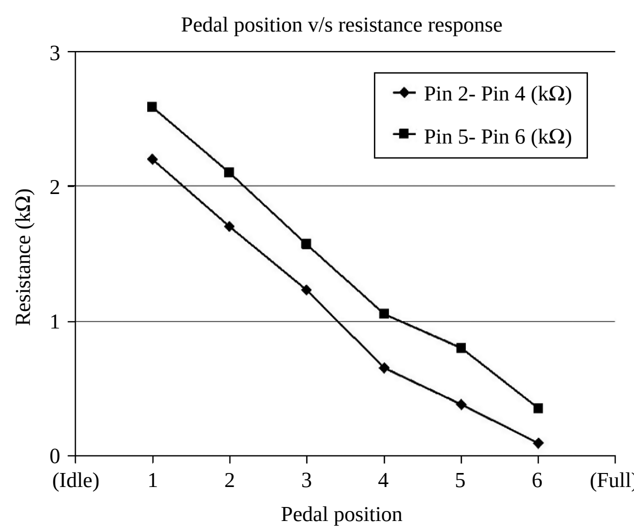


Figure 6 Pedal position and corresponding resistance responses



a double-sided circuit board with semi-circular traces on one surface. On the opposite surface of the circular circuit board is a rotary disc with two pairs of spring contacts attached to it. In the assembled state, the spring contacts are in contact with the circular traces on the circuit board. Each spring contact terminates with three fingers, as shown in Figure 7 and in the environmental scanning electron micrograph in Figure 8. The two pairs of spring contact terminal fingers are electrically

Figure 7 Interior cavity of the APPS

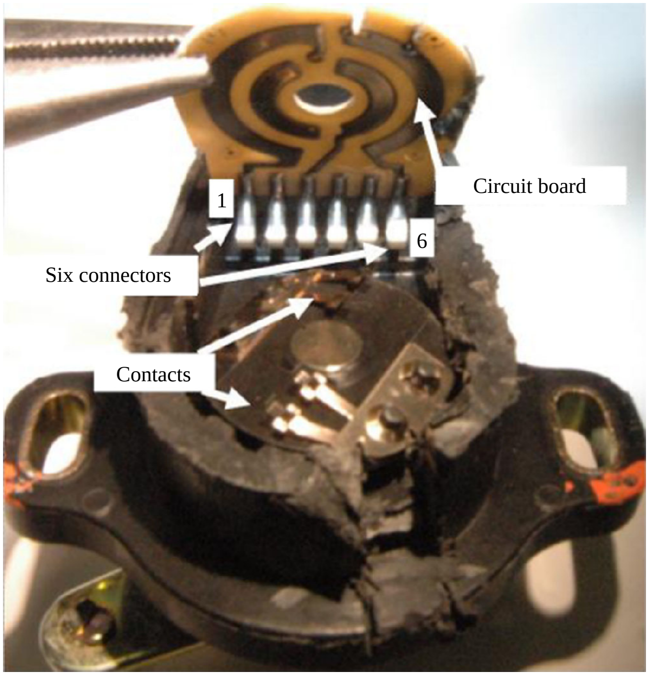
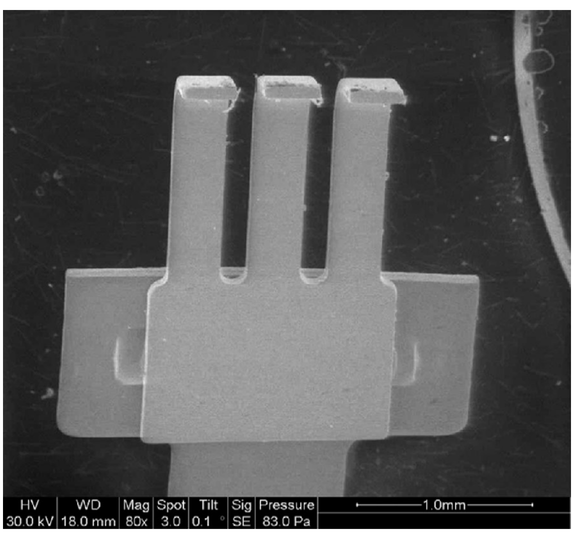


Figure 8 An environmental scanning electron micrograph showing the spring contact terminal fingers

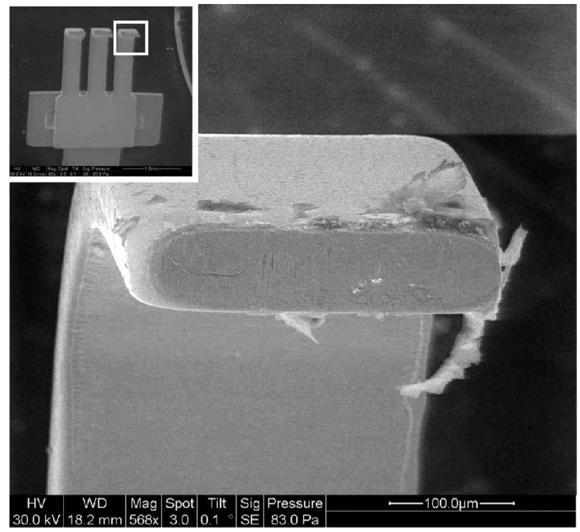


isolated from each other, but are connected to a metal shim that is mounted on the rotary disc.

Examination of the spring contacts, using X-ray fluorescence analysis, revealed a polymetallic plating film of palladium, gold, platinum, bismuth and silver over a base of copper. Examination of one of the four slider contact fingers identified particulate debris (Figure 9), which has the potential to cause erroneous outputs to the behaviour shown in Figure 6.

The semi-circular traces on the double-sided circuit board are constructed of a layer of silver filler particles that is sandwiched between a 30- to 40-μm thick filled graphite film and gold-plated copper trace, with a nickel underlayer. The semi-circular traces on the circuit board connect

Figure 9 Environmental scanning electron microscopic image of a single finger of the contact



to external wires through flat copper terminals that extend from the cavity through the housing to form a molded six-pin male connector. Six flat copper spring leads plated with 1.4-μm-1.8-μm thick tin connect the board terminals to the connector terminals. The edge-to-edge distance between spring leads measured approximately 1.1 mm. The tin-plated spring leads were attached with eutectic tin-lead solder to the pads of the circuit board and brazed to the copper connector terminals in the plastic housing, as shown in Figure 10.

Inspection of the terminals in the accelerator position sensors from the 2002 and 2005 Camry models revealed tin whisker formations (Figures 11-13). A tin whisker is a conductive hair like structure, which can grow spontaneously from tin-finished surfaces. Tin whiskers are known to cause electronic failures (Arnold, 1959) which is a reason for prohibiting the use of tin finishes in safety related applications (AAA, 2006; BBB, 2006). The failure risks include current leakage and shorting due to bridging of adjacent conductors (Ganesan and Pecht, 2006; Fang *et al.*, 2006a, 2006b, 2007;

Figure 10 Accelerator position sensor board connections

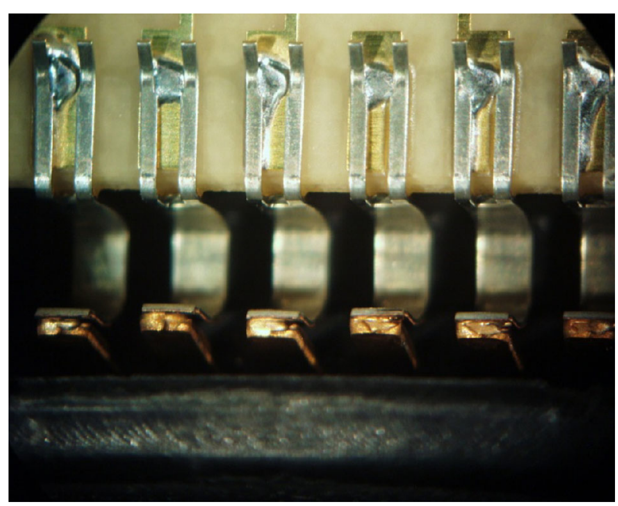


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Figure 11 Tin whiskers on the surface of the acceleration position sensor board connection terminals of the 2005 Toyota Camry

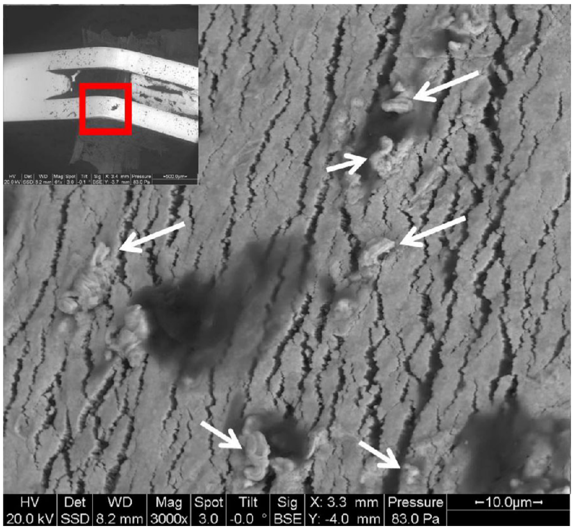
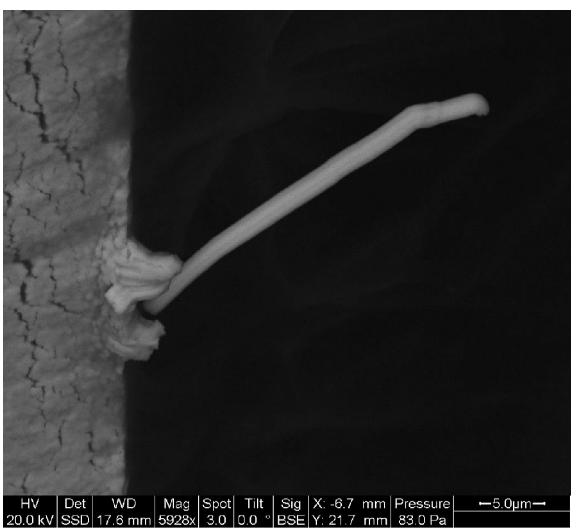


Figure 12 Tin whisker on the edge of an acceleration position sensor board connection terminal of the 2002 Toyota Camry

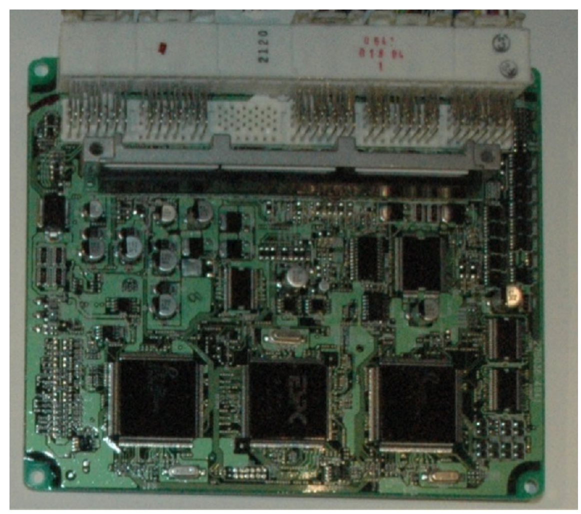


Han *et al.*, 2010; Fukuda *et al.*, 2006, 2007; Shibutani *et al.*, 2008, 2009a, b; Mathew *et al.*, 2009; Woodrow and Ledbury, 2006; Calce Tin Whisker Risk Calculator, 2005).

In addition to the APPS, the construction of the ECM, shown in Figure 14, was examined. The ECM contains surface mount electronic devices connected with tin-lead solder to a multi-layer PCB. The majority of the board was conformally coated, but the coating thickness ranged from about 90 μm to being absent in certain regions of the assembly, including the edges of the large perimeter leaded devices. Regions of the PCB with no coverage or non-uniform conformal coating leave the underlying electronic devices unprotected and susceptible to particulates, ionic contaminants, moisture and tin whiskers.

Figure 13 Tin whisker on the surface of the acceleration position sensor board connection terminal of the 2002 Toyota Camry

Figure 14 Engine control module



With poor conformal coating, tin whiskers can easily grow and cause shorting and current leakage.

Interconnect terminals of the perimeter leaded devices were found to be plated with tin. In addition, tin plating was found on terminal pins of the edge connections. As previously discussed, tin-finished leads can grow tin whiskers which can lead to unintended electrical shorts.

Discussion and conclusions

Failure of the ECU can result in inability to start the vehicle, inability to change throttle level, reduced efficiency in engine performance, uncontrolled acceleration and/or deceleration. Failure in electronic equipment can be related to software errors and/or physical failures of one or more electrical devices.

In some cases, failures produced by these mechanisms may be permanent; in other cases the failures may be intermittent. Intermittent failures may appear while the product is operating and disappear when the product is taken off line to trace the failing elements. The intermittent failures are sometimes termed "no-failure-found" failures, or "cannot duplicate" failures (Qi *et al.*, 2008; Williams *et al.*, 1998).

Of particular concern in the analyzed assemblies was the use of a tin finish. Tin finishes can produce metal whiskers that are conductive and capable of creating unintended current leakage paths. In our analysis, a significant number of tin whiskers were found. Using the calceWhiskerRiskCalculator (Calce Tin Whisker Risk Calculator, 2005) to assess the failure risk posed by observed tin whisker formation on the conductor pairs, it was determined that the potential for a tin whisker shorting failure was 140/1 million. Considering the number of vehicles on the road, it is expected that this would present a significant safety hazard.

Tin whiskers can produce intermittent failures in electronic circuitry that are often impossible to detect. First, tin whiskers can move significantly during their growth or under the influence of an electrostatic field. That is, a whisker can cause an electrical short or leakage current condition, for example, under a powered-up condition or a change in potential, and then become electrically open under some other powered situation. In cases where a tin whisker creates an electric short, joule heating may also cause the whisker to melt thereby removing the previously existing short. Finally, whiskers are very delicate and are prone to break if the loading conditions are right.

Tin whiskers are extremely difficult to detect. High magnification is necessary to detect them and appropriate lighting conditions are critical in the microscopic analysis. Because of the intermittent nature of tin whiskers, failures are not always detectable. It is highly likely that tin whiskers could induce a failure that is later undetected. For this reason, best practices for electronics design stipulate that tin not be used as a plating material. It is very questionable why the National Highway Traffic Safety Administration, with a stated mission to "save lives, prevent injuries and reduce economic costs due to road traffic crashes, through education, research, safety standards, and enforcement activity", has not come out with a requirement that no electronics use pure tin as a material component, since the potential for tin whiskers presents an unreasonable and unnecessary risk.

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About the authors

Bhanu Sood is Director of the Test Services and Failure Analysis (TSFA) Laboratory at the Center for Advanced Life Cycle Engineering (CALCE), University of Maryland. He received MS degrees in Advance Material Processing and Materials Science from National Technical University and George Washington University, respectively. His research areas include electronic materials characterization, failure mechanisms in printed circuit board (PCB) materials, electronic supply chains and counterfeit electronic parts detection techniques. Prior to joining CALCE in 2005, Bhanu Sood worked at the US Naval Research Laboratory (NRL) in Washington, DC. He is a member of the IEEE and ASM.

Michael Osterman is a Senior Research Scientist and the CALCE Consortium Director at the University of Maryland. He is involved in the development of simulation-assisted reliability assessment software and simulation approaches for estimating time to failure of electronic hardware under test and field conditions. Dr Osterman is one of the principal researchers in the CALCE effort to develop simulation models for temperature cycling fatigue of Pb-free solder. He has been involved in the study of tin whiskers since 2002 and has authored several articles related to the tin whisker phenomenon. Michael heads the development of simulation-based failure assessment software at CALCE and is a member of the IEEE, ASME, and SMTA.

Michael Pecht is Director of the CALCE Electronic Products and Systems Center at the University of Maryland. Professor Pecht has an MS in Electrical Engineering and an MS and PhD in Engineering Mechanics from the University of Wisconsin at Madison. He is a Professional Engineer, an IEEE Fellow, an ASME Fellow and a Westinghouse Fellow. He has written numerous books on electronics products development and on the electronics industry in South East Asia. Michael served as Chief Editor of the *IEEE Transactions on Reliability* for eight years and on the Advisory Board of *IEEE Spectrum*. He is currently the Chief Editor for *Microelectronics Reliability*. Michael Pecht is the corresponding author and can be contacted at: pecht@calce.umd.edu