

# Prognosis of Connector Disconnection Using a Canary-Based Approach

Xinyu Du<sup>1</sup>, Atul Nagose<sup>2</sup>, Aaron Bloom<sup>2</sup> and Timothy Julson<sup>2</sup>

<sup>1</sup>General Motors Global R&D, Warren, MI, 48090, USA

*Xinyu.du@gm.com*

<sup>2</sup>General Motors Company, Warren, MI, 48090, USA

*Atul.nagose@gm.com*

*Aaron.bloom@gm.com*

*Timothy.d.julson@gm.com*

## ABSTRACT

The electrical connector disconnection is a common problem in automotive systems. It can be caused by bad design, manufacturing issues, ageing in harsh environment, or low product quality. An imminent disconnection during driving may result in severe safety issues. A loose connection manifests itself as intermittent faults of various vehicle components, which is hard to diagnose and likely leads to unnecessary component replacement or dealership revisit. In order to predict the connector disconnection, a low-cost canary-based approach is proposed in this paper. A shortened male terminal is employed to foretell the loose factory terminals in the same connector housing. The dimension and placement of the shortened terminal are theoretically and experimentally investigated to achieve optimal performance. The proposed solution is tested and compared to other common diagnostic and prognostic approaches, including inductance-, capacitance-, resistance-based approaches, time domain reflectometry, and frequency domain transmissometry, using a connector bench test setup. The placement variation test and the accelerated vibration test are performed to simulate the long-term real driving scenario as well. It's shown that the proposed solution is capable of predicting connector disconnection robustly before the vehicle functionality is affected.

## 1. INTRODUCTION

An electrical connector is an electro-mechanical device for joining multiple electrical circuits. A modern vehicle consists of approximately 300 electrical connectors and 2,400 terminals. Connector disconnection has been identified as

one of the major contributors to the warranty cost. Disconnection can be induced by bad design, manufacturing issues, ageing in harsh environment, or low product quality. For instance, the clicking sound of latching a connector is hard to be noticed by workers in the noisy environment at the assembly line. The connector may be partially connected but not fully latched. Such a connector can pass the end-of-line test, but will become disconnected sooner or later after the vehicle is sold.

A loose connector may cause intermittent faults, which are onerous to diagnose. A customer may notice certain problems while driving over a rough road. However the failure is hard to replicate at the dealership, i.e. CCND (Customer Concern Not Duplicated) which makes the customer and the dealership frustrated. When a loose connector becomes permanently disconnected, the related subsystems or components may malfunction, and potentially cause safety issues or customer walk-home scenario.

A variety of techniques have been developed to diagnose connectivity issues in past decades. One category is based on the electrical properties such as inductance, resistance, conductance, capacitance or impedance (Chung, Amarnath and Furse, 2009). If a wire becomes open or a connector is disconnected, the resistance and inductance of the circuit will increase, while the capacitance will change depending on the dimension or placement of the wiring or the connector. When the wire gets shorted to the ground, the resistance and capacitance will become very small. The fault type and/or location can be determined accordingly.

Another category of techniques is based on the characteristics of transmission or reflection signals generated from an active or passive electrical signal through the circuit (Furse, Chung, Lo and Pendalaya, 2006). There are two fundamental techniques, namely time-domain transmissometry (TDT) (Will & Rolfes, 2013) and time-domain reflectometry (TDR).

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TDT monitors the transmission characteristics of an electrical signal to determine the fault severity, while TDR (Furse, et al., 2006; Shi & Kanoun, 2014; Smail, Pichon, Olivas, Auzanneau and Lambert, 2010; Smail, Hacib, Pichon and Loete, 2011; Okada, Nishina, Ataka, Hashimoto, Irisawa and Imamura; 2015) measures the amplitude and the timing of the reflected signal to determine the location and the type of the fault. A typical active TDR/TDT setup includes a signal generator and a detector with very high sampling rate, because the electrical signal propagates at a speed close to the speed of light. The excitation signal can be a pulse, a step signal, or a more complex signal. Whenever the signal encounters an impedance discontinuity, it will get reflected and transmitted partially. The discontinuity could happen due to a change in wire material, thickness, number of strands, connector disconnection, or wire open/short. The amplitude of the reflected signal depends on the change of impedance. And the distance from the monitor to the discontinuity location can be calculated based on the time that takes the injected pulse to return. In the preventive maintenance of power distribution network or telecommunication network, TDR is commonly used to reduce the diagnostic time/cost by avoiding digging up the kilometers-long cable. Sequence Time Domain Reflectometry (STDR) and Spread-Spectrum Time-Domain Reflectometry (SSTDR) (Furse, Smith and Safavi, 2005; Smith, Furse and Gunther, 2005) are the techniques derived from TDR, and the faults are identified by observing reflected spread spectrum signals. SSTDR is successfully used on aviation wiring for both preventative maintenance and fault localization. The method has also been shown to be useful to capture and locate intermittent faults. In addition to the TDR/TDT, the transmission signal can be analyzed in the frequency domain as well, which is called frequency domain transmissometry (FDT) or frequency domain reflectometry (FDR) (Furse, Chung, Dangol, Neilson, Mabey and Woodward, 2003; Chung, Furse and Pruitt, 2005; Tsai, Lo, Chung and Furse, 2005).

Although these approaches have been proven to be able to detect or locate open faults or short faults, no study is found that any of these have the capability of predicting an electrical fault especially connector disconnection. In this paper, the existing techniques including resistance-, capacitance-, and inductance-based approach, TDR, and FDT, will be studied and compared in terms of prognostic capability. The implementation cost will be considered in the comparison as well. Furthermore, a canary-based prognostic approach is proposed in this paper. The word “canary” is originated from coal mining systems for warning of the presence of hazardous gas using canaries (Vichare and Pecht, 2006). Because the bird is more sensitive than human-beings to the hazardous gas, the sickness or death of the canary is an indication of the hazardous gas. In the proposed canary-based prognostic approach, one terminal in the connector will be designed as a canary to predict connector disconnection. To our best knowledge, this is the first paper to apply the canary approach

in connector disconnection prognosis. The walkout rate for a loose connector rate is also analyzed through a vibration test with a given driving profile.

The remainder of this paper is structured as follows. The canary-based solution will be proposed and described in Section 2. The comparison between the existing methods and the canary-based approach using a connector bench is presented in Section 3. The experimental results on the robustness performance and prognostic capability for the canary-based approach are shown and discussed at the end.

## 2. CANARY-BASED APPROACH FOR CONNECTOR DISCONNECTION PROGNOSIS

An electrical connector consists of a connector housing and terminals. Both housing and terminals include a male end (plug) and a female end (jack). An example of a vehicle in-line connector is shown in Fig. 1. It is an unsealed 10-way connector made by Delphi. The male and female terminals are installed in the cavities in the male and female connector housing, respectively. The terminals are locked in the housing with the blue plastic pin shown in Fig. 1. There's a latch on the female connector, which holds the male connector housing in the fully engaged position to prevent the connector from becoming loose. In terms of connectivity, the connector has three states shown in Fig. 2. When a connector is installed correctly, the connector is fully engaged, mechanically locked, and electrically connected as shown in Fig. 2(a). In this state, the male terminal makes an electrical contact with the spring-like tongue in the female terminal. The electrical signal can be robustly transmitted through the connector/terminals. When the connector is partially engaged, the connector is mechanically loose, but electrically connected (Fig. 2 (b)). This is a precursor to the state of being electrically disconnected. In this precursor state, the intermittent disconnect may happen depending on the severity of disengagement. Fig. 2(c) shows the connector that is fully disengaged and electrically disconnected. In this state, the vehicle components related to this connector/terminals will malfunction. Normally the distance from the electrically connected state to the electrically disconnected state is only several millimeters, which depends on the design of the connector as shown in Fig. 3. This distance that the male terminal overlaps with the female terminal, called over-travel, exists for every connector to account for the manufacturing tolerances, e.g. dimensional variation in the terminals and housing.

In order to predict connector disconnection, a feasible solution should meet at least three requirements. First of all, the solution should be capable of predicting disconnection with enough lead time. Secondly, the cost of the solution must be low since the solution is required to be onboard for each connector in each vehicle. Thirdly, the solution should be sensitive to capture intermittent faults with the duration of a few milliseconds, and robust enough to other disturbance in



Figure 1. The Delphi 10-way connector. The housing is on the top and the terminals are shown at the bottom. The left is the male end and the right is the female end.

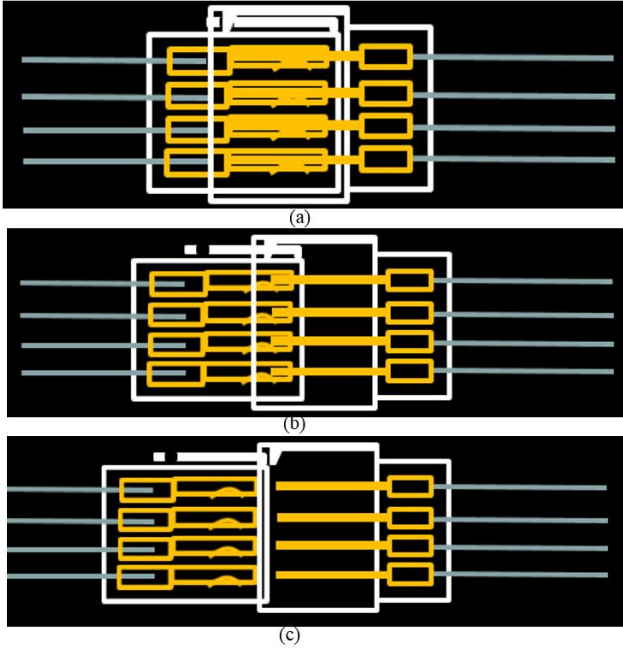


Figure 2. Three states of connection connectivity. (a) Engaged and electrically connected (b) Loose but electrically connected (c) Disengaged and electrically disconnected.

the fully engaged state. Based on above considerations, we propose a canary-based approach. The proposed solution employs one shortened terminal in the connector as a canary to predict the loose state of the whole connector. A canary terminal compared to a factory male terminal is shown in Fig. 4. The canary terminal may be applied to an existing non-critical circuit or be an additional terminal if there is an empty cavity in the connector to be monitored. As the connector is disengaged, the circuit connected to the canary terminal will become open before other important circuits connected to the factory terminals are affected. The proposed solution essentially converts prognosis to diagnosis.

The length of the short terminal is integral to the performance of the proposed solution. Considering the robustness requirement, the length of a short terminal should be at least more than the length of a factory terminal minus the designed

over-travel. This will ensure an electrical connection when the connector is fully engaged and latched. On the other hand, the shorter the length of the canary terminal, the more sensitive the solution would be to predict the disconnection. Therefore, it's necessary to accurately calculate the length of the shortened canary terminal. This length is determined by the dimension and tolerance of the design of the connector and terminals. Here, the specification of Delphi 10-way inline connector is shown in Fig. 5. The nominal over-travel is shown as "X" in Fig. 5. The tolerance of "X" can be determined from the tolerance of other dimensions as follows.

First of all, the distance between the female housing front edge and the point of contact  $L_1$  can be calculated as below,

$$L_1 = B + C - A \quad (1)$$

where  $A$  is the distance from the radius tangent to the tip,  $B$  is the distance from the tip to the backstop, and  $C$  is the distance from the terminal backstop to the cavity backstop.

The distance between the male terminal backstop and the lock ramp  $L_2$  can be calculated as,

$$L_2 = I + H + G + E - F \quad (2)$$

where  $E$  is the distance from the front edge to the front shroud,  $F$  is the distance from the front edge to the lock ramp,  $G$  is the distance from the male connector lock ramp to the female connector lock,  $H$  is the distance from the lock ramp to the shroud base, and  $I$  is the distance from the shroud base to the cavity front.

The distance between the male terminal backstop and the point of contact  $L_3$  is

$$L_3 = L_2 - D + L_1 = -A + B + C - D + E - F + G + H + I \quad (3)$$

where  $D$  is the distance between the back stop and the front edge.

Last, the terminal over-travel  $L_4$  can be determined as,

$$L_4 = J - L_3 = A - B - C + D - E + F - G - H - I + J \quad (4)$$

where  $J$  is the distance between the front cavity to the forward stop.

Based on the previous discussion, the minimum length of a short terminal must be greater than the length of the factory terminal  $J$  minus the over-travel  $L_4$ , which is  $L_3$ . Here, the point of contact between the male and female terminals lies just at the tip of the male terminal. Considering the robustness, the tip length should be added to make the contact



Figure 3. Over-travel distance for a connector. The green color indicates the over-travel area. The orange color indicates the connector housing. The gray color are for terminals. The purple color corresponds to the wire.

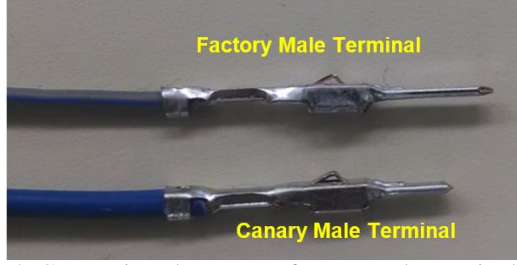


Figure 4. Comparison between a factory male terminal (above) and a canary male terminal (below).

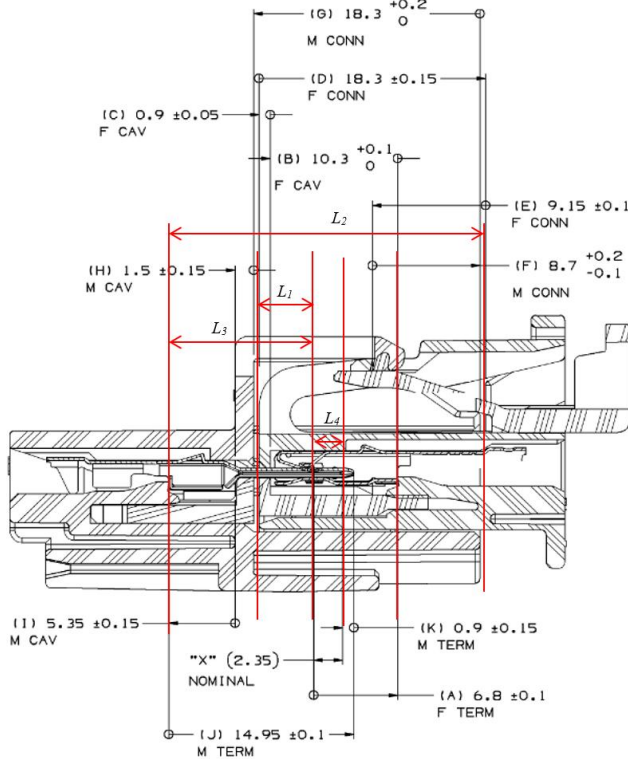


Figure 5. Dimensions of a Delphi 10-way connector as well as corresponding tolerance.

point at the body of the terminal, which means the minimum length of a canary terminal is  $L_3 + K$ , where  $K$  is the distance between the forward stop to the backward stop.

Taking the tolerance into account, the minimum length of a short terminal is between  $\text{MIN}(B + C + E + G + H + I + K) - \text{MAX}(A + D + F)$  and  $\text{MAX}(B + C + E + G + H + I + K) - \text{MIN}(A + D + F)$ .

The design dimensions and tolerance for a Delphi 10-way connector are shown in Table 1. The minimum length and maximum length are calculated from the tolerance and nominal values shown in Fig. 5. The nominal length of a factory male terminal ( $J$ ) is 14.95mm. The length of a canary terminal should be 13.85mm with the point of contact at the terminal body. With this length, the canary terminal is guaranteed to make a consistent electrical connection with the connector fully engaged. The canary terminal is able to

Table 1 Dimension and tolerance stacking for the Delphi 10-way factory terminals and the connector housing

Label	Description	Min Length	Max Length	Nominal
A	Radius tangent to Tip	+ 6.7	+ 6.9	6.8
B	Tip to back stop	- 10.3	- 10.4	10.3
C	Term back stop to Cav back stop	- 0.85	- 0.95	0.9
D	Back stop to front edge	+ 18.15	+ 18.45	18.3
E	front edge front shroud	- 9.05	- 9.25	9.15
F	front edge to lock ramp	+ 8.6	+ 8.9	8.7
G	M conn lock ramp to F conn lock	- 18.3	- 18.5	18.3
H	lock ramp to shroud base	- 1.35	- 1.65	1.5
I	Shroud Base to front cavity	- 5.2	- 5.5	5.35
J	Front cavity to forward stop	+ 14.85	+ 15.05	14.95
K	Forward stop to back stop	- 0.75	- 1.05	0.9
Overlap without the tip		3.5	1	2.35
Length of the canary terminal to make contact on the body		11.55	13.85	12.6
Length of the canary terminal to make contact on the tip		10.8	12.8	11.7

make prediction 1.1 mm prior to the connector disconnection.

### 3. COMPARISON ON PROGNOSTIC CAPABILITY FOR DIFFERENT APPROACHES

In order to prove the prognostic capability of the proposed solution, and compare it with other existing approaches in the literature, some experiments have been conducted, and described in this section. We evaluated the state-of-art techniques including the inductance-, capacitance-, resistance-based approach, TDR, and FDT for comparison. The theoretical analysis for each approach is performed first, followed by the test results.



### 3.1. Experiment Setup

A customized connector bench is built to test the prognostic capability for different approaches. With the bench it is able to precisely engage the male and female connectors and check the connectivity at any engagement distance. For the test purpose, the connector latch is removed. The bench, shown in Fig. 6, includes a motor, a linear actuator, and a potentiometer. It employs a linear drive to engage/disengage the connector, and measure the engagement distance which the linear drive is also able to convert the rotation motion from the motor to the linear motion. The potentiometer is used to measure the exact engagement or disengagement distance. The output signal of the potentiometer is transmitted to the DSpace Micro-Autobox. To make engagement and disengagement movement, a bi-directional control circuit is designed to supply power to the motor. When a constantly high voltage is applied, the linear drive will move with the speed as high as 11mm/sec. A small pulse can be used to move the linear drive with single step as small as 0.1mm. An emergency stop switch is designed to ensure that the drive can be powered off manually if all other safety checks fail. Control algorithms are developed and implemented in the DSpace Autobox to drive the linear drive. The DSpace Autobox is also connected to a computer to display all the signals in the software DSpace ControlDesk. The engagement or disengagement action can be triggered from the ControlDesk as well.

In order to compare different approaches, the following equipment are used. The Exetech 380193 LCR meter is used to measure the resistance / inductance / capacitance value for the connector. The Agilent 86100C oscilloscope with 58754A TDR/TDT module is used to measure the TDR response. The Agilent E4438C ESG vector signal generator is used to generate excitation signal in radio frequency for the FDT approach. The Agilent N9020A MXA signal analyzer is used to analyze the high frequency transmitted signal.

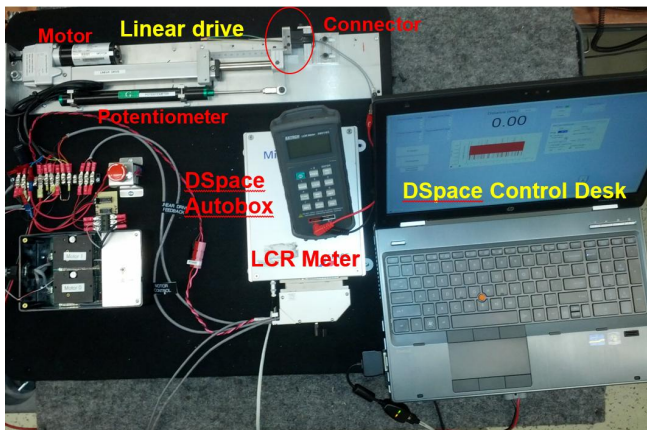


Figure 6. The customized connector test bench consisting of a DSpace Autobox, control circuits, a linear drive, the connector to be tested and a computer.

### 3.2. Comparison of Existing Approaches

#### 3.2.1. Inductance-, Capacitance-, and Resistance- based Approaches

The LCR meter is employed to evaluate the inductance-, capacitance-, and resistance-based approaches. The meter is connected to the male side of the connector. Here two pairs of terminals of the connector are connected to the positive and negative probes of the LCR meter, respectively. The female side of the connector is set up in different ways depending on the type of approach to be evaluated. For capacitance-based approach, the wires on the female side are open. This is because the shorted wires make capacitance measurement be close to 0 all the time. When the resistance- or inductance- based approach is evaluated, the wires on the female side are shorted to each other because open wires cause the infinite value. The inductance/ resistance / capacitance results are shown in Figs. 7, 8 and 9, respectively. In order to make sure the test results be reliable and valid, we repeat the test 3 times on each of 3 sets of terminals for all approaches we discuss in this section.

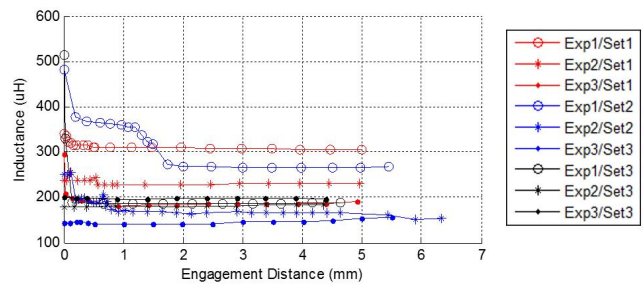


Figure 7. Inductance change along with the engagement distance. Zero engagement distance means the connector is just electrically disconnected. Three sets of terminals are used in the tests, and are denoted as Set 1, 2 and 3, respectively. The test is repeated on each set of terminals for 3 times shown as Exp 1, 2, 3, respectively. For simplicity, the same legend of Exp and Set are used in the Figs. 8-9, 11-13 without more explanations.

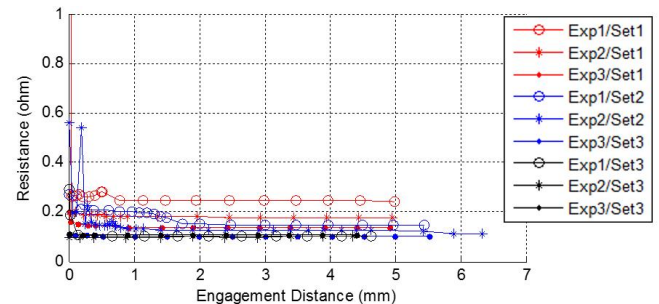


Figure 8. Resistance change along with the engagement distance. Zero engagement distance means the connector is just electrically disconnected.

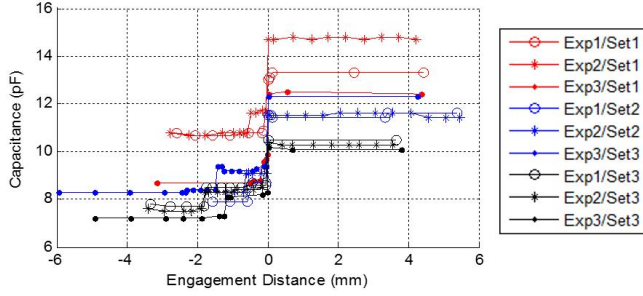


Figure 9. Capacitance change along with the engagement distance. Zero or negative engagement distance means the connector is electrically disconnected.

In Fig. 7 and Fig. 8, the resistance value and inductance value are only plotted when the connector is engaged. The infinite value is expected when the connector is open. At the beginning of each test, the engagement distance is reset to zero in order to minimize the effect of measurement error due to the initial position of the terminals in cavities. The variance of measurement in different tests could be attributed to the contact resistance between the alligator clips of LCR meter and the wires, or between two short wires on the female side. From the tests, we can conclude the resistance value and the inductance value are almost constant when the connector is mechanically loose but electrically connected. This can be explained from the wire inductance and resistance characterization. The self-inductance of a pair of parallel wire (Serway and Jewett, 2014) is

$$L = \frac{\mu_0 l}{\pi} \left( \ln \left( \frac{d}{a} \right) + \frac{Y}{2} \right) \quad (5)$$

where  $\mu_0$  is the magnetic constant,  $a$  is the wire radius,  $d$  is the distance between two wires,  $l$  is the length of the wire,  $Y$  is a constant depending on the current. When a connector is mechanically loose but partially engaged, all parameters are almost the same except for the length  $l$  becoming smaller due to the engagement. However, the maximum change of  $l$ , i.e. over-travel, is much smaller than the total length of the wires. Therefore,  $l$  is almost a constant.

The resistance of the wire can be calculated as follows,

$$R = \frac{\rho l}{A} \quad (6)$$

where  $l$  is the length of wires,  $A$  is the cross-sectional area and  $\rho$  is the electrical conductivity of the material.  $\rho$  and  $A$  are almost constant during the engagement.  $l$  is slightly changed up to several millimeter over-travel distance when the connector is engaged. Therefore, the resistance keeps almost constant as well.

For the capacitance test, three distinct levels can be found in Fig. 9 as the connector goes from the fully disengaged state to the fully engaged state. Here the capacitance test circuit involves two pairs of terminals in the connector, where one pair of male and female terminals connects to the positive probe of LCR meter, and another pair is connected to the negative one. The capacitance value stays at relatively high

level when the connector is fully engaged, i.e. both pairs of terminals are electrically connected. The middle level is due to the state when only one pair of terminals has made the electrical contact. Due to the movement of the terminals, this state could last from 0 to 2mm. The lowest capacitance value occurs when both pairs of terminals are fully disengaged. This can be explained from the capacitance characterization for a pair of parallel wires (Serway and Jewett, 2014) as below,

$$C = \frac{\pi \epsilon l}{\ln \left( \frac{d}{2a} + \sqrt{\frac{d^2}{4a^2} - 1} \right)} \quad (7)$$

where  $l$  is the wire length,  $d$  is the distance between two wires,  $a$  is the wire radius,  $\epsilon$  is the permittivity of the material. Obviously all parameters keep almost the same except for the length of the wire  $l$ . When the connector is fully disengaged, both pairs of terminals are electrically disconnected. The wires connected to the other side of the connector are disconnected from the capacitance measurement circuit. So the length of wires is shortest, and therefore the capacity measurement is low. When the connector gets engaged from the fully disengaged position, the wire length is increased since the part of wires connected to the female terminal is connected through the connector. Once both terminals are electrically connected, the capacitance value stays constant as the change of the wire length is much smaller than the total length of the wires.

Overall, when the connector is loose, there is no consistent pattern with respect to resistance, inductance or capacitance. It takes anywhere from 0.1-2 mm to settle down to a constant level. Hence these methods are good for detecting disconnection but unreliable to predict disconnection.

### 3.2.2. TDR

The signals of TDR at different engagement distances are shown in Fig. 10. The x-axis is the time, and the y-axis is the reflected signal voltage. Similar to the capacitance response discussed in 3.2.1, the signals are bunched in three distinct groups with little variation within each group. The reflection curve shifts towards the right along with the change of engagement states as the length of wires is increased. Similar to the capacitance test, the middle level again belongs to the case when only one pair of terminals has made contact as the connector is partially engaged.

The amplitude of the reflected signal and the reflection time are plotted at each engagement state for three sets of terminals in Fig. 11 and Fig. 12, respectively, which are determined using the peak point in Fig. 10. As discussed above, it can be observed that the reflection time becomes longer with three discrete levels and so does the amplitude.

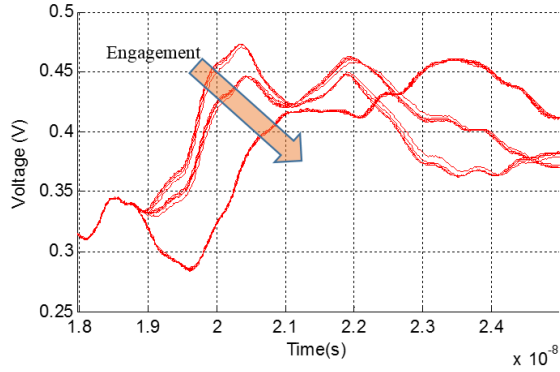


Figure 10. TDR signals for one terminal pair. Each curve represents the TDR signal at one engagement distance.

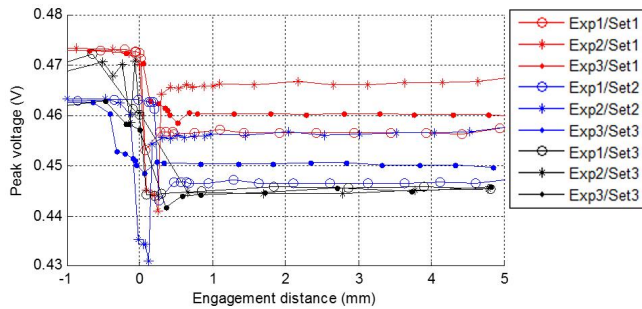


Figure 11. The relationship between the TDR peak voltage and the engagement distance for 3 sets of terminals with 3 repetitive tests. Zero or negative engagement distance means the connector is electrically disconnected.

### 3.2.3. FDT

To test an FDT approach, a high frequency sine wave signal is injected to the male side of the connector. The transmitted signal from the female end is analyzed using a signal analyzer. The peak amplitude of the signal is measured at different engagement distances. Signals with different frequencies have been tested and no different pattern is observed. Therefore, we arbitrarily choose the signal with 2 dBm at 250 MHz which is shown in Fig. 13. The effect of cross interference at such a high frequency is noticeable. The placement of input and output wires changes the FDT signal level considerably e.g. 15 dBm are observed between experiment 1 and experiment 2 from Fig. 13. However, the pattern of signals at different engagement distance is similar to other approaches. Two distinct levels of signals are found corresponding to the full engagement and partial and full disengagement. Overall, the FDT approach is only good for fault detection.

### 3.3. Test on the Canary-based Solution

The proposed short terminal solution has been tested on the bench. A few factory terminals are manually shortened by different lengths to make canary terminals. The terminal is first cut under the microscope with a caliper. Then the tip

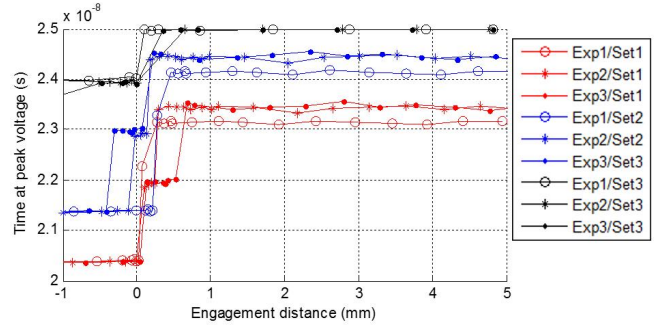


Figure 12. The relationship between the TDR reflection time at the peak point and the engagement distance for 3 sets of terminals with 3 repetitive tests. Zero or negative engagement distance means the connector is electrically disconnected.

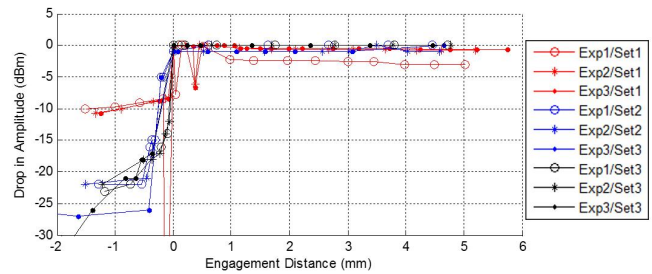


Figure 13. FDT signal changes along with the engagement distance. Zero or negative engagement distance means the connector is electrically disconnected.

is coined similar to the factory terminals using a grinder.

As shown in Table 1, the length of a factory terminal is 14.95mm. The over-travel of the factory terminal is measured to be 4.33mm on the bench, which is consistent with the theoretical analysis of the over-travel with the tip. The terminals would never make electrical contact if they are cut by more than the maximum over-travel. Therefore, the male terminals are cut by amounts less than the maximum over-travel, namely 1.63mm, 2.6 mm and 3.75 mm, respectively. The circuit shown in Fig. 14 is used to detect the connectivity for one factory terminal and three canary terminals. In principle, the connector/terminals act as a switch for the circuit. The LED indicates if it is open or closed.

The connector is fully engaged at the start of the test. The status of each terminal pair is monitored as the connector is being walked-out. The distances where each terminal become open are recorded and shown in Table 2. The minimum detectable looseness is the minimum disengagement distance where the terminal becomes open. The shortest canary terminal D3 is able to predict the connector disconnect when the connector has walked-out by 0.58mm. While the longest canary terminal D1 can predict the connector disconnect when the connector has walked-out by 2.8mm. The factory terminals are still engaged and they would remain electrically connected for a further 1.5mm walk-out. These numbers are



consistent with the over-travel that we calculated in the previous section.

In summary, only the proposed canary-based solution is able to predict connector disconnection. All existing techniques are effective in detecting the connector open, however ineffective for predicting it. When the connector is loose, these fault signatures, e.g. the resistance values, are not consistent between different tests or between different sets of connectors. Therefore the correlation to the engagement distance cannot be established. These inconsistencies might be caused by the following reasons, in addition to the measurement error. First, the terminals can move tenths of millimeters inside the cavity. The exact position of terminals for each test will affect the engagement distance as measured with the bench. Another factor could be terminal wearing out. Terminals are only designed to perform for around 10 engagement cycles. The coating on the terminals wears off with more tests, causing changes in fault signatures. The third reason is the variance of the connector placement and the associated wires. This is because the inductance- or capacitance- based approaches and TDR/FDT are sensitive to the wire shape and distance between the wires.

From the cost perspective, the proposed canary-based solution only requires an additional voltage measurement circuit to detect if the short terminal is disconnected. The cost for one short terminal mainly comes from the tooling, which is very low comparing to the cost of the circuit. For other solutions, the circuit complexity is much higher than that of the canary-based solution. A circuit with the very high sampling rate is required to calculate the impedance or TDR response. The cost is much higher accordingly.

#### 4. ROBUSTNESS TEST AND VALIDATION

In this section, two robustness tests are conducted to evaluate the performance of the proposed solution. In order to simulate scenarios at assembly line, various placements for the connector and wires are applied. Then an accelerated vibration test is completed by mounting the connector with the canary terminals on a vibration table.

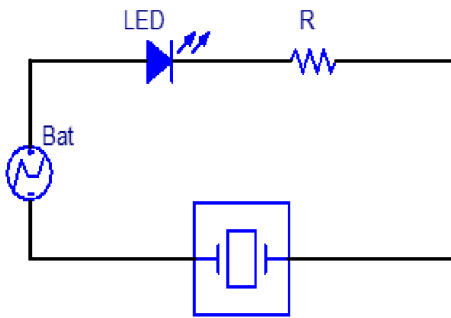


Figure 14. The circuit used to test the proposed canary-based solution.

Table 2. The list of the terminals used in the test.

Terminal	Length (mm)	Minimum Detectable Looseness (mm)
Normal	14.95	4.33
D 1	13.32	2.8
D 2	12.35	1.73
D 3	11.2	0.58

#### 4.1. CONNECTOR PLACEMENT VARIATION TEST

From Fig. 5, one can observe that the male terminal is able to slightly move within its corresponding cavity. The movement can be caused by either forcing the terminal wire towards or against the connector, or twisting the connector housing in different directions. A robust solution is expected not to show any false alarm when the connector is fully engaged and latched regardless of these movements

Due to the symmetric nature of the problem, in this test, only the terminals at the right half part are tested, the results of which are shown in Fig. 15. The gray block is the connector latch. The connector housing is twisted up, down, left and right. And the terminal wires on both male and female connector are pulled away from the connector or pushed towards the connector. The results are recorded in Table 3. “C” means the connector is electrically connected, and “D” means the connector is electrically disconnected.

In the test, the terminals are tested over a range of lengths limited by the theoretical calculations done earlier. The minimum length to make any contact is found to be 10.8mm. This is when the contact is made on the tip of the male terminal after accounting for all design tolerances. From Table 3 it can be seen that, at 10.8mm, disconnect is not shown for the center cavities but is shown for corner cavities. This is expected as the corner cavities experience the most strain when bending the wire harness connected to the connector. The same behavior is observed for the lengths of 11.0, 11.2 and 11.4mm. This leads us to the conclusion that 10.8 mm is the most sensitive length for the non-corner cavities while still being robust to false positives. The non-corner cavities are less sensitive by about 0.8mm compared to the corner cavities. The center cavities are more robust to bending, and the corner cavities are more sensitive to bending. When the terminal length is more than 11.6mm, the solution is robust for all test scenarios. Thus 11.6 mm is the most sensitive length while still being robust to false positives. Please note that the data in this test is only from one set of terminals/connector, considering the part to part variance, one can conclude that the theoretical calculation of the canary terminal length shown in Table 1, 13.85mm, is the best choice in terms of both robustness and sensitivity.



		3	4	5
		8	9	10

Figure 15. Connector placement variation test for the Delphi 10-way connector. Each grid indicates a cavity of the connector. The cavity number in the grid shows the terminal used in the test. The cavity without a number indicates the terminal is not used in the test. The latch is drawn in grey color.

Length (mm)	Cavity	T1	T2	T3	T4	T5	T6	T7
10.8	3,4, 8,9	C	C	C	C	C	C	C
	5	D	D	D	D	D	C	D
	10	C	C	C	D	D	C	C
11	3,4, 8, 9	C	C	C	C	C	C	C
	5	C	C	D	C	D	C	D
	10	C	C	C	D	D	C	D
11.2	3,4,8,9	C	C	C	C	C	C	C
	5	C	C	C	C	D	C	C
	10	C	C	D	C	C	C	D
11.4	3, 4, 8, 9	C	C	C	C	C	C	C
	5	C	C	D	C	C	C	C
	10	C	C	D	C	C	C	D
11.6 11.7 12.6	3,4,5, 8, 9, 10	C	C	C	C	C	C	C

Table 3 Test results for the connector placement variation test. “C” means the connector is electrically connected, and “D” means the connector is electrically disconnected, The columns T1- T7 are corresponding to normal, twist up, twist down, twist left, twist right, push in and pull out tests, respectively

#### 4.2. VIBRATION TEST

The proposed solution is also evaluated in an accelerated vibration test to simulate the normal driving behavior. The solution is expected not to show any false positive for a fully engaged connector when the connector is vibrating. Furthermore, the walkout rate for a loose connector can be found out from the test, and is critical to evaluate the prognostic capability in terms of remaining useful life.

##### 4.2.1. Test Setup

A temperature chamber with a vibration table is employed which is manufactured by Thermotron. The whole setup is shown in Fig. 16. The connector is mounted on the vibration table through a Christmas tree clip. The wire is clamped on the table at the given distance away from the connector, which is consistent with the assembly line. The wires are

routed out of the vibration chamber and connected to a customized test box for data logging.

A profile of vibration stress test is used in this test which is shown in Fig. 17. This is a standard connector test for corrosion and fretting. It has been observed that the vibration profile on a real vehicle follows a similar pattern even though with smaller amplitude.

A customized test box, shown in Fig. 18 is built to record voltage up to 5 terminals at 1ms sampling rate. The test box employs an Arduino circuit to sense and record the voltage. The data and associated time stamps are logged to a MicroSD card. It also includes a battery to power up the whole test box, several LEDs to indicate the status of each terminal being tested, and 10 ports to connect both ends of 5 terminals. When the male and female terminals are electrically connected, the voltage measurement is 0. When the terminal pair is open, the voltage will become 2.8V. The status of each channel is shown through a green LED which connects to the digital port on the Arduino as well. A MicroSD card breakout board is connected to the SPI connector on Arduino. The length of the ribbon connecting the two is kept short so as not to adversely affect the data transfer.

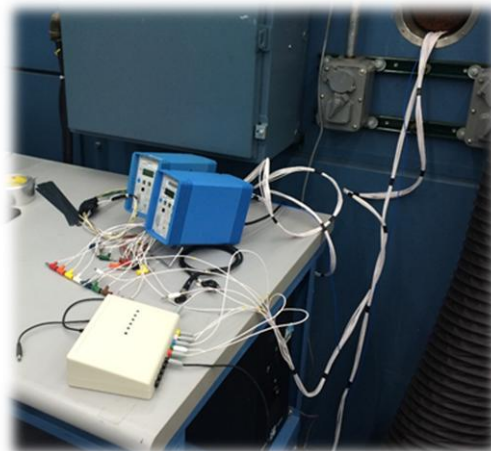


Figure 16. Setup for the vibration test. The upper figure shows the connector is mounted on the vibration table, and the lower figure shows the test box and wiring connection.

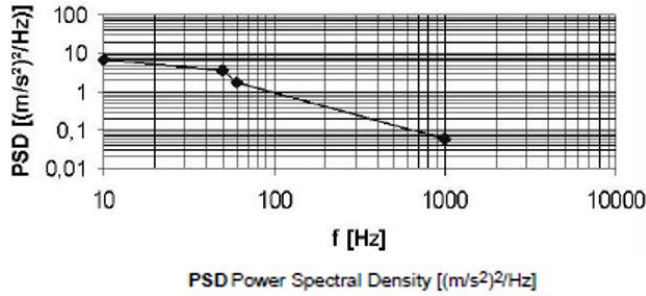


Figure 17. The profile of vibration stress test used in this vibration test

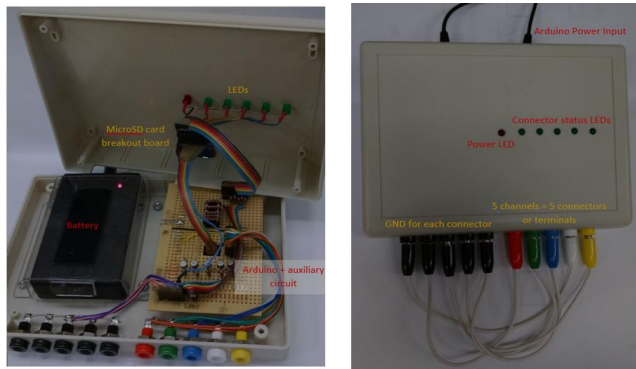


Figure 18. The Arduino-based test box with 5 pairs of channels to record the connectivity data. The left figure shows the circuit and battery, and the right figure shows the connection and LEDs.

#### 4.2.2. Test Results

The cut length of canary terminals for this test is shown in Fig. 19. In this test, the corner cavities are filled with factory terminals. The top center three cavities are filled with canary terminals with the length of 10.8mm (cut by 4.1mm). The bottom three cavities are filled with canary terminals with the length of 11.7mm (cut by 3.2 mm). Since the analysis on the cavity impact has been performed in the section 4.1, the placement of terminals in this test is arbitrarily selected.

At the beginning of the test, the connector is fully engaged and latched. After a few days of vibration, all terminals including canary terminals are still electrically connected. This validates that our solution is robust in the vibration scenario. After unlatching the connector, the shortest three canary terminals become open at around 0.5mm of walkout distance. The other three short terminals become open at around 1.3mm walkout distance. At 3.6mm walkout distance, almost all terminals become open. The overall test results are shown in Fig. 20, where red indicates electrically disconnected and green represents electrically connected. This observation is in line with our previous analysis. Please note that it normally takes long time for connector to come loose. We manually walked it out a few millimeter between each test which are indicated in the dashed line in Fig. 20.

The solid line corresponds to the walkout happened during the test. The overall walkout is linear along with the test time. The total test time including the skipped part is about 2000 hours.

From the time and walkout distance, the walkout rate is calculated as 571 test hours/mm. This means that cutting the terminal by 1mm will achieve the prediction capability of 571 test hours. Since the rough road vibration profile is used in this test, the 571 test hours can be regarded as 571 driving hours on rough roads. Assuming 2 hours of rough road driving per day, 571 hours are equivalent to 9.5 months of prediction time.

The voltage recorded during the test is shown in Fig. 21. From the detection circuit we know that the voltage measurement is 0 V for a fully latched connector, while 2.8V voltage means the connector is electrically disconnected. Some noisy voltage points are shown in the transition between fully disconnected to fully connected state. This indicates the average voltage can be used as the connectivity indicator. The voltage over each 2 minutes of data is averaged and shown as the red dots in the Fig. 21.

During the walkout test, it is difficult to control the movement of the terminals within their corresponding cavities. It would have taken too long to reset each terminal at each step. To fully study this impact, short tests are done within the duration of 10 minutes each. The terminal wire is either pulled away from the connector or pushed into the connector. These represent the two bounds for the terminal position within the cavity. The connector is walked out manually over the range of 0-4.5mm with at least 0.25mm step. Consistent with our previous connector placement variation analysis when the terminals are pushed into the connector, they stay connected for a longer walkout than when they are pulled away from the connector housing. It took 0.2-1mm of further walkout to get the terminal to become open when the terminals are pushed in as compared with the respective terminal are being pulled out. This is inherent to the design of connector cavity and terminals. It should be taken into account when the length of the canary terminal is being

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0	4.1	4.1	4.1	0
0	3.2	3.2	3.2	0

Figure 19. The cut length of different terminals for the tested connector (in mm). The black bar indicates the connector latch.

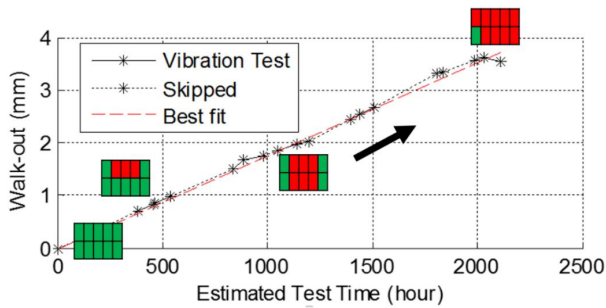


Figure 20. The test results for the vibration test. Green color indicates electrically connected and the red color indicates electrically disconnected.

decided upon. Fig. 22 shows a comparison of average voltage between a factory terminal and the two canary terminals considering this placement variation. As mentioned earlier when the terminal is pulled out, the terminal comes open 0.2-1mm before with the terminal pushed in. The canary terminal becomes open at a smaller walkout distance as compared to the factory terminal. That difference in the walkout is close to the length by which the canary terminal are cut by.

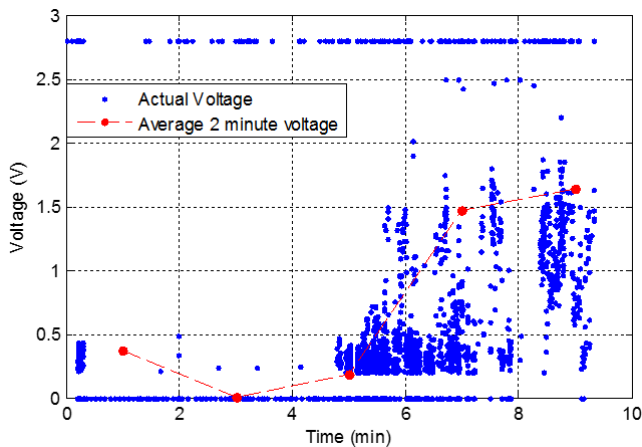


Figure 21. The voltage data recorded by the test box for one test. The average voltage is plotted in the red color.

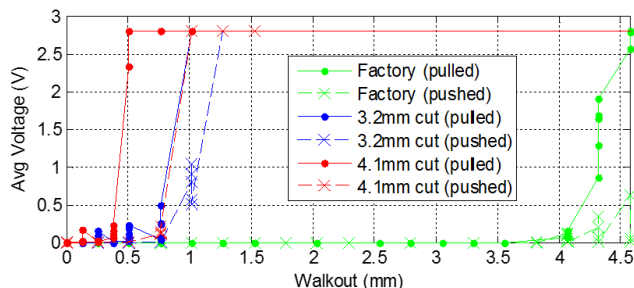


Figure 22. The effect for placement variance with pushed wire and pulled wire for different length of terminals. Green color: factory terminal, blue color: 11.7mm canary terminal (3.2mm cut), and red color: 10.8 mm canary terminal (4.1 mm cut)

## 5. CONCLUSION

Connector disconnection is one of the most common failures in automotive industry. Predicting connector disconnects before the vehicle functionality is affected can greatly reduce the number of walk home scenarios, reduce warranty cost and improve safety ratings. The canary-based approach using a shortened male terminal has been developed for connector disconnection prognostics in this paper. The solution is validated and compared with other approaches using a Delphi 10-way connector on different benches. There are some key findings summarized as below, (1) The proposed canary-based approach is able to predict connector disconnection while other state-of-art diagnostic approaches can't, e.g. resistance/ inductance/ capacitance-based, time domain reflectometry/ transmissometry, and frequency domain transmissometry. (2) The maximum or optimal shorten length can be calculated from the design dimension and tolerance with a proposed procedure. (3) It is found the walkout rate of a loose connector (Delphi 10-way) is 1mm every 971 test hours, which is equivalent to 1 mm/ 9 month from the accelerated vibration test. (4) The optimal length for a shortened terminal is 1 mm shorter than the factory terminal (Delphi 10-way) based on both theoretical analysis and vibration test. (5)The placement of the shortened male terminal impacts the sensitivity of the solution. The solution for the shortened terminal using corner cavities away from the latch is more sensitive than the one using center cavities.

The proposed solution is being evaluated for production implementation. A comprehensive robustness analysis for this solution and the remaining useful life estimation based on this solution will be our next steps. As a critical part of the integrated vehicle health management, the connector disconnection prognosis, along with other subsystem/ component prognostics, will provide valuable information to customers, service providers, and production engineers.

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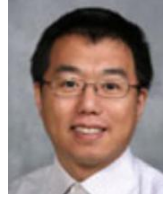
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## BIOGRAPHIES



**Xinyu Du** received the B.Sc. and M.Sc. degrees in Automation from Tsinghua University, Beijing, China, in 2001 and 2004, respectively, and the Ph.D. degree in electrical engineering from Wayne State University, MI, USA, in 2012. He has been working in General Motors Global R&D Center, Warren, MI since 2010, and currently holds the senior researcher position in vehicle system research lab. He has published 29 peer review papers and holds 9 patents. He has 9 US or international patents pending and 7 GM internal inventions. His research interests include fuzzy hybrid system, vehicle health management, vehicle electronics and data mining. He has been serving as an associate editor for *Journal of Intelligent and Fuzzy Systems* from 2012 and served as a lead guest editor for *Advances in Fuzzy Systems*. He was a member of IEEE fuzzy system competitions technical committee in 2009 and 2011. He received the Boss Kettering Award from General Motors for his contribution in integrated starting system prognosis in 2015.



**Atul Nagose** received B.Tech in Mechanical Engineering in 2007 from Indian Institute of Technology Madras, India. He completed his M.S. in Mechanical Engineering specializing in Control Systems in 2010 from The Ohio State University, US. He has been working at General Motors R&D, Warren MI since 2010, currently as a Vehicle Systems Engineer in the Vehicle Health Management group. He has 5 US or international patents pending and 2 peer reviewed papers.



**Aaron Bloom** received a Bachelor's of Science in Electrical Engineering from Rensselaer Polytechnic Institute (2013) and an Master's of Business Administration from the Michigan Ross School of Business (2017). He has been working at General Motors in the power and signal distribution systems group since 2013 and currently holds a design release engineer position on the next generation alpha platform. He has filed four patents jointly with the research team related to vehicle health management and connector prognosis.



**Timothy Julson** received the B.S. in Mechanical Engineering at Michigan Technological University in 1981. Currently he is a BFO at General Motors.