Road Test and Reliability Analysis of Automotive Electronic Modules

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Abstract--**This paper describes a road test using a printed circuit board (PCB) used for automotive applications. In order to characterize the vibration stresses, a series of road tests were conducted which included different automobiles and road conditions such as city and highway. During the road tests, a comprehensive data acquisition system was used which can record temperature, acceleration, driving speed, strain, etc. Strain sensors are mounted on the PCB module close to a major IC component. Experimental results show a clear correlation between acceleration, speed and road conditions. The stresses obtained from vibration during the road tests are generally much smaller compared to the lab tests on a vibration table. However, the maximum board strain may be significant and worthy of further studies. The objective is to assess the fatigue risk of solder joints during field use to warranty operation of 10k hours in 15 years.**

Key Words: Automotive, Road Rest, Reliability, Vibration, Strain, Solder Joint

I. INTRODUCTION

Electronic devices and systems are widely used in automobiles and have become increasingly important due to the recent popularity of self-driving cars (SDC). The reliability requirements of automotive electronics are superior to typical commercial products primarily due to safety concerns.

The environmental stresses in automotive electronics are much more complex than a typical consumer application such as a residential/office environment or in general under mild and relatively benign environmental conditions. In the automobile field, the environmental stresses are caused not only from the temperature/humidity swings but also from vibration and other mechanical stresses. Usually, the temperature can swing from -40 °C to +65 °C for ambient temperature, and the relative humidity can be 50% to 90%. To understand the reliability of electronic modules used in automobiles, it is essential to characterize use conditions in terms of vibration, acceleration, etc. Proper reliability tests may be designed based on the field stress conditions.

Vibration is one of the most important stresses for automotive applications because the vehicles are being operated under constant and varying vibration conditions. However, the vibration experienced in the automotive applications is random and its responses are far more complicated than sinusoidal vibration. The damage severity of a PCB assembly from a vibration stress may be described by the vibration magnitude as well as the board structure. To characterize random vibration responses, a power spectral density (PSD) is commonly used to specify a random vibration regime. The acceleration spectral density (ASD) is collected and processed by a data acquisition system. The root mean square acceleration (G_{rms}) is the square root of the area under the ASD curve in the frequency domain. The G_{rms} value is typically used to describe overall energy of a particular random vibration event and is a statistical value used in mechanical engineering for structural design and analysis purposes.

To characterize a vibration response during transportation, the severity of vibration may be classified by PSD values by three levels as follows [2,3]:

a. Benign (<0.005 g^2/Hz)
b. Normal (0.005~0.03 g^2/Hz)
c. Worst (>0.03 g^2/Hz

Vibrationdata[4] has performed a lot of measurements and published PSD data for various automobiles shown in Table 1. As can be seen from Table 1, a clear correlation can be observed between weight and Grms. Comparing different axes, the vertical Grms value are highest in most cases. That indicates the vertical vibration should be the focus for the stress analysis.

Table 1 Grms measurement data from various automobiles by Vibrationdata [4]

Automobile	weight, (lbs)	Grms—Longitu-dinal	Grms--Lateral	Grms-Vertical
Ford Van	8600	0.054	0.121	0.207
Dodge Van	8550	0.053	0.252	0.231
Freightliner	16000	0.066	0.12	0.377
Mid-size car	4500	0.091	0.108	0.144
Pickup truck	6000	0.12	0.111	0.259

The PSD demonstrates how hard the vehicle is vibrating but it doesn't give any direct damage information about the forces experienced by the test unit. To find the stress magnitude of a structure during random vibration, one efficient way is to use finite element analysis (FEA). FEA has been successfully employed to calculate the stress of a BGA (ball grid array) solder joint [5, 6, 8, 10]. Empirical data are collected and a correlation has been derived between vibration stresses and solder joint life shown in Equation 1 [5~8].

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The expected fatigue life of a solder ball typically exceeds 10,000 cycles under vibration conditions. The failure is mainly attributed to the stress due to high-cycle fatigue as characterized by Basquin power law relation:

$$\sigma = a(2N_f)^{-b} \tag{1}$$

where σ is the stress amplitude which can be calculated by FEA. a is the fatigue strength coefficient, b is the fatigue strength exponent, Nf is the reversal[WU1] to failure [3~8]. The corresponding equation as deduced from Steinberg [10] determines a = 109.6 and b = 0.10 for eutectic solder. Yu [5,10] has demonstrated those coefficients from sinusoidal vibration test for Sn-Ag-Cu (SAC) solder joints by regression. With the calculated Von Mises stress (σ) from FEA and fatigue cycles (Nf) from vibration tests, the constants a and b were determined to be 64.8 MPa and 0.1443 for SAC305, and 152.2 MPa and 0.2079 for SAC405 through linear regression analysis. The fatigue strength exponent for SAC305, b = 0.1443, is much higher than that of Steinberg (b = 0.10), which indicates a more conservative estimation on the stress impact.

In this study, the road test was conducted using different auto vehicles and different load conditions. In order to understand responses of a PCB assembly during vibration, direct measurement of acceleration and PCB strain are conducted together with the vehicle speed. To understand the stress of the PCBA solder joints, an FEA model is composed for various speed and road conditions as well as different vehicle models. The road conditions may include city, mountain terrains, highway and local roads. During the road tests, strain sensors are mounted on the PCB module close to the graphics processing unit (GPU) chip and the whole module is installed in a navigation box—similar to the one used in the field.

To compare the road test results, lab tests using a random vibration tester are also utilized. Tests following ISO 16750-3 [11] and others may be used. The purpose of this work is to develop an appropriate model to correlate the lab tests with the real road driving so that a qualification test can be justified.

II. EXPERIMENTAL SETUP AND METHODOLOGIES

The test unit is a PCB assembly with fcBGA (body size = 23x23mm, pitch = 0.65mm, pin count = 664). The PCB is multilayer with a thickness of 1.2mm as shown in Fig. 1a. The fcBGA is mounted in the center of the board. Two tri-axes strain gauges are mount on the two corners of the fcBGA. An accelerometer is mounted on the board and a data logger is used as shown in Fig. 1b, which has a build-in battery & WIFI with 32 channels for data recording. This board is mounted in a box with metal frame and then mounted to an automobile by screw attachment. To test the worst case condition inside an automobile, the box is mounted in the trunk which is close to the rear wheels. Several types of auto vehicles are tested but only the results from two models are shown in Table 2. An accelerometer is also mounted on the enclosure for comparison. A typical vibration response is shown in Fig. 1c.

The vibration response will be analyzed using a fast Fourier transform (FFT) and the PSD curve shall be reported. Finite element analysis (FEA) is employed to simulate the solder joint stresses at a given PSD curve. During the vibration, the corner solder joints are experiencing the highest stress across the whole package. These solder joints are investigated with fine mesh to improve the accuracy. The maximum von Mises stresses from the critical layer are reported from these corner balls. To assess cracking risk, the critical layer is close to the intermetallic compound (IMC) and the maximum stresses are volume-averaged as a stress index. This stress is used to estimate the life of the solder joint of the component.

To assess the severity of the vibration, PCB strains are also tested during the road test. The strain gauges are mounted on two corners of the fcBGA [12]. The maximum and minimum principal strains are reported.

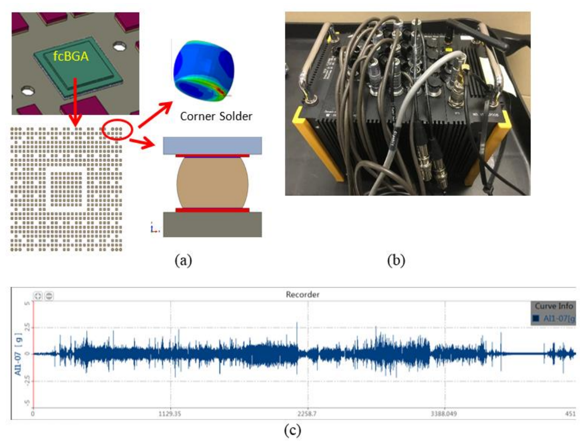


Fig. 1. Unit under test in auto vehicle: FEA model of fcBGA and solder joint in PCB (a), data logger (b) and acceleration response with time (c).

Table 2 Automobiles used in this study

Auto ID	Description	Build Year	Weight
A1	Compact, Sport	2015	3600lbs
A2	Mid-size	2015	3300lbs

III. RESULTS AND DISCUSSION

The response of the road test from two automobiles is shown in Fig. 2~5. In Fig. 2, the speed vs. time (s), PSD vs. frequency (Hz) and acceleration vs. time (s) are plotted respectively for A1-highway. Similar plots are shown for A1-local in Fig. 3. For automobile A2, the corresponding results are shown in Fig. 4 and 5. From those figures, one can see clearly the acceleration is a direct response of the speed change. i.e., there is an acceleration spike when the automobile stops. However, the acceleration values are also dependent to road conditions and types of automobiles, which is described by PSD curves in Fig. 6. Fig. 6 lists PSD curves obtained from road tests on highway and city-local for both vehicles, which shows insignificant difference between those two conditions for automobile A1. For A2, however, it shows that the PSD in highway is higher than the one in city-local. That may be due to differences of the road condition and driving speed. Table 3 lists all test parameters and analysis results. In Table 3, the average speed for A2-highway is about 49mph while A2-city-local is about 22mph. The peak acceleration and total Grms of A2-highway is much higher as comparing to that of A2-city-local.

To assess the road test severity, the PSD curve from lab tests per ISO 16750-3 is also shown in Fig. 6. It clearly shows that the lab test represents a highly accelerated condition because the acceleration is around 100x as compared to the one from the road tests. The maximum volume average stress for a critical solder joint is calculated by FEA and the results are also listed in Table 3. As shown in Table 3, the max. von Mises stress values for all road tests are around 1MPa or below, while the value for the lab test is 31.6 MPa. To predict the fatigue life of fcBGA during vibration, Equation (1) is used and b is set to 0.1443. The predicted life of road tests would be in the magnitude of 1e+10 [WU2]or higher. For a typical automobile requirement, a test time of minimum 60 hrs is needed [12] which would give a huge safety margin for the field application (10k hours, 15 years' requirement) from a purely vibration stress aspect.

To further assess the failure risk of the road test, the other approach is to study the board strain. Fig. 8 shows the strain values from cases 1-4 which is a snap shot of the strain data from the road test. Fig. 9 summarizes the strain values in all cases in the whole trip test. Interestingly enough, the PCB strains are quite high during the road especially in automobile A1 which has reached about 400ue. The PCB strain on A2 is less than 200ue. The PCB strains at A1 may be close to the failure risk region as defined by IPC9704 [12]. This does show that a sport car may cause high bending on the PCB if the board is mounted close enough to the wheels. It is worthy of further studies in this area.

Road test is a complex task which involves a lot of setup but is most meaningful for development of a test standard as well as evaluating the failure risk. In order to collect statistically meaningful data, different test boards and auto vehicles are needed.

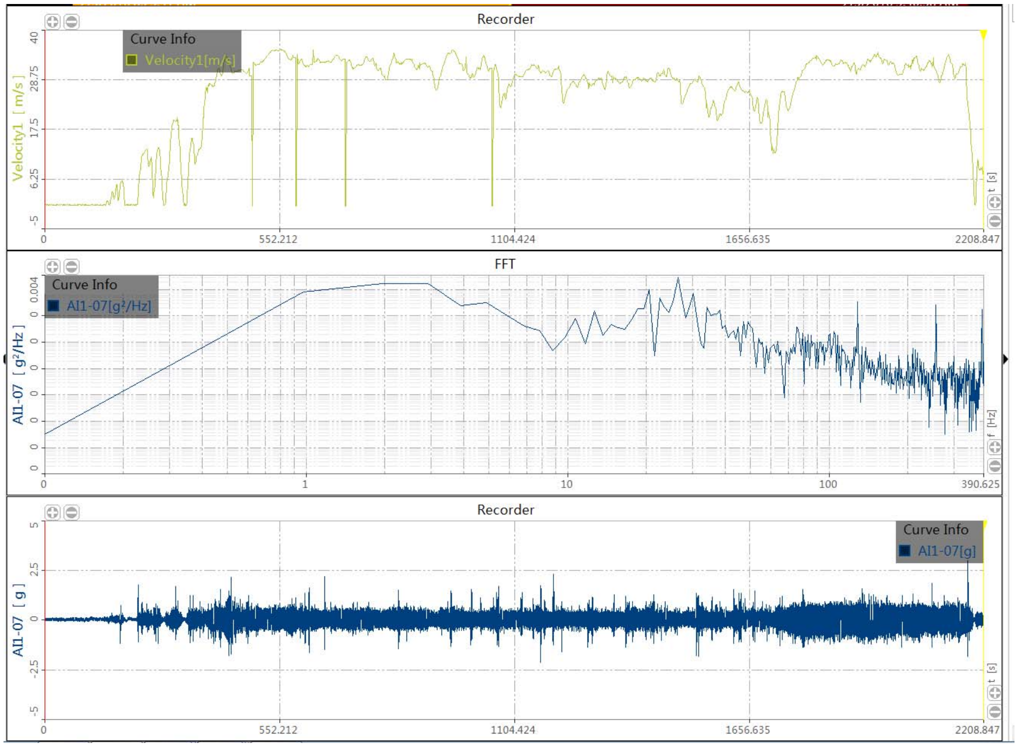


Fig. 2 Speed, PSD and Acceleration response for A1--Highway

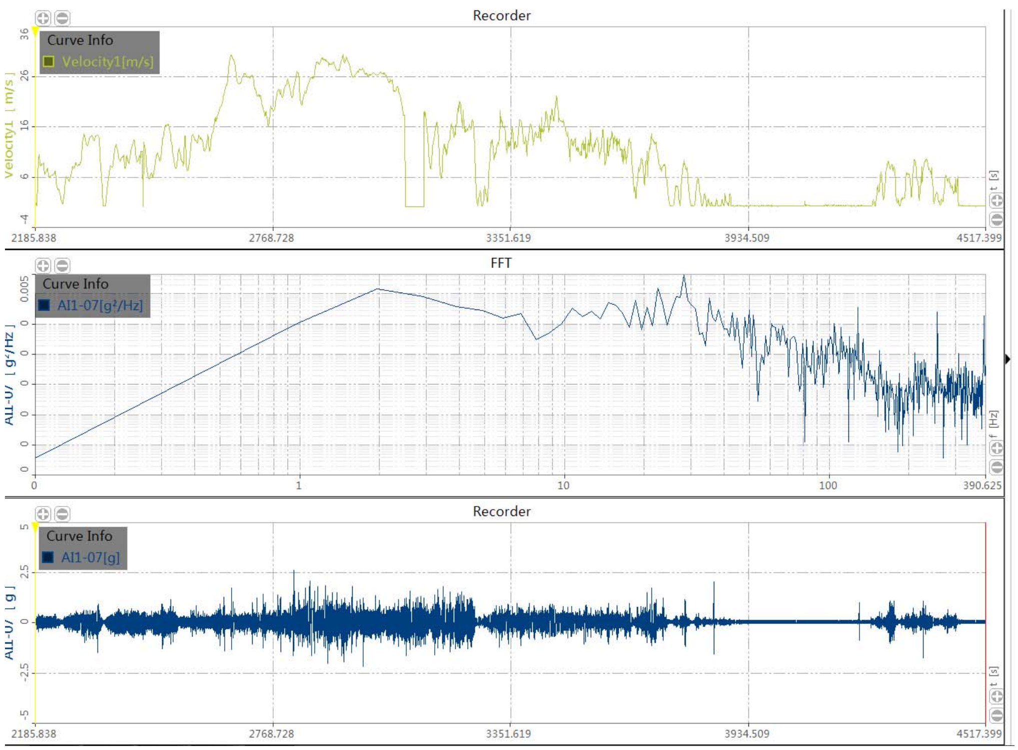


Fig. 3 Speed, PSD and Acceleration response for A1—City

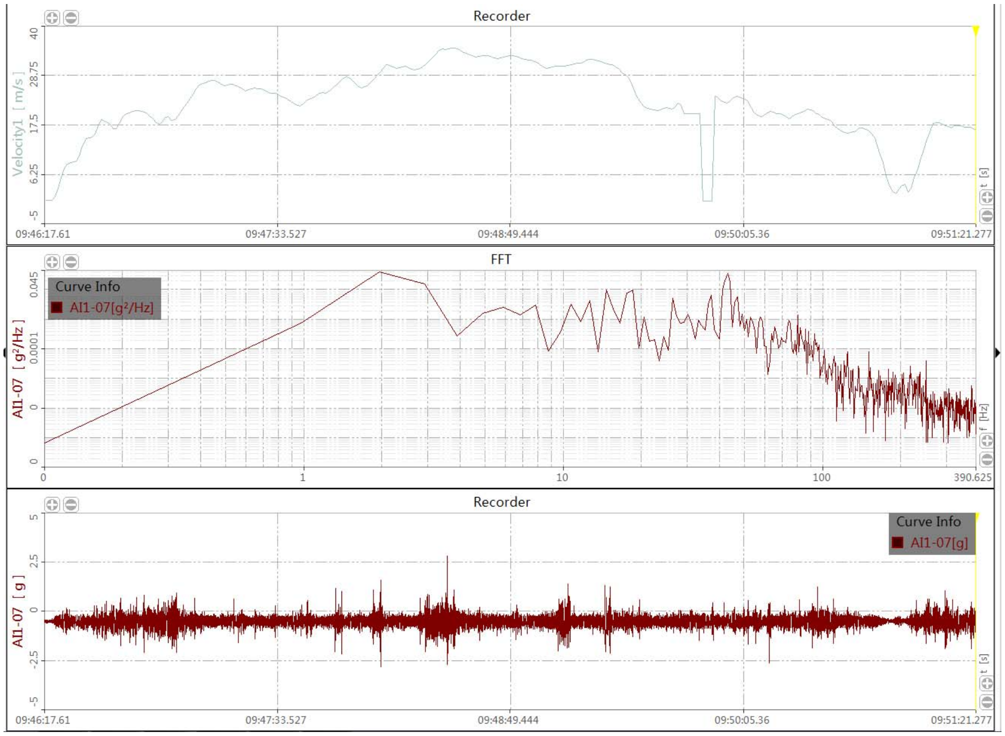


Fig. 4 Speed, PSD and Acceleration response for A2--Highway

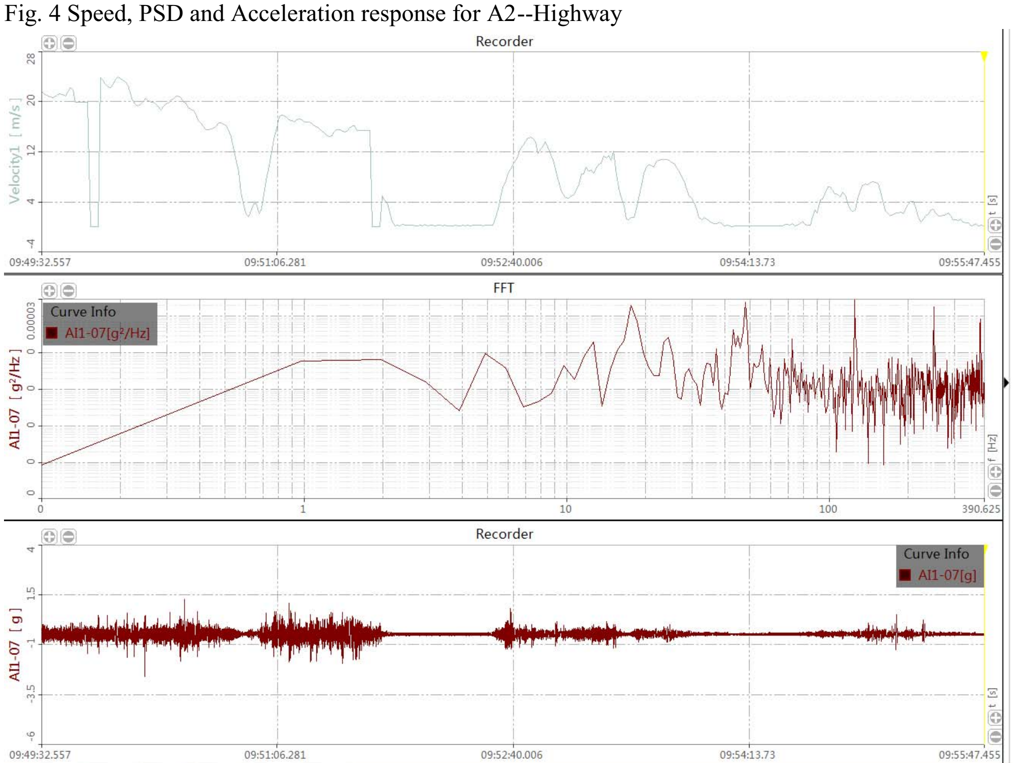


Fig. 5 Speed, PSD and Acceleration response for A2—City

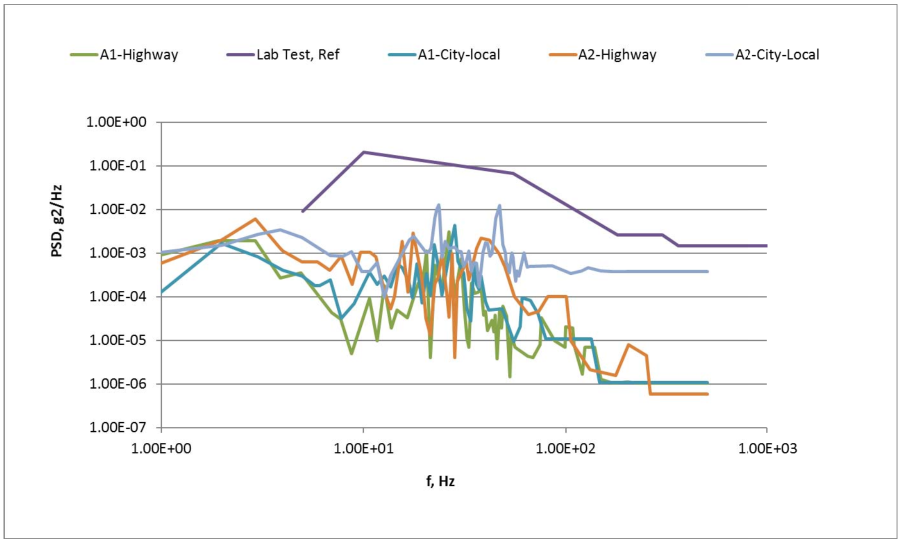
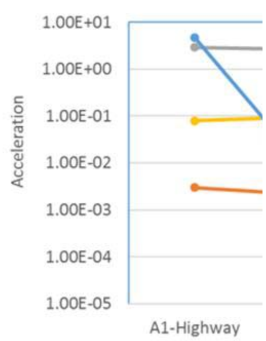


Fig. 6 PSD Comparison for various road conditions.

Table 3 Summary of the road test as a comparison with a lab test

ID	Auto code	Road Conditions	Avg Speed, mph	Peak PSD, G2/hz	Peak A, G	Grms	PCB Strain Range, ue	**Max. Avg. mises, Mpa**	**Nf, normalized**
1	A1	Highway	56.67	0.003	2.944	0.083	135	0.769	1.554E+11
2	A1	Local_City	23.4	0.004	2.567	0.1	98.02	0.777	1.446E+11
3	A2	Highway	49.67	0.006	2.765	0.154	72.92	0.755	1.765E+11
4	A2	Local_City	22.27	0.0002	1.346	0.024	70.23	0.242	4.716E+14
5	A3	Highway	65	0.008	0.2	0.056		0.442	7.233E+12
6	A3	Local_Dirty	34	0.038	0.6	0.16		1.04	1.915E+10
7	Ref	Lab test	NA	0.2		3.14		31.6	1

Note: Data for Auto code A3 is based on test data from Vibrationdata [4].



[WU3]

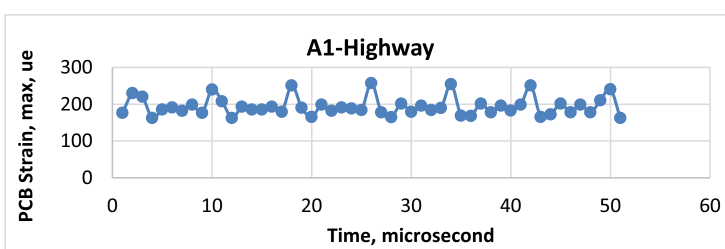


Fig. 7 Acceleration comparison of automobile A1 and A2.

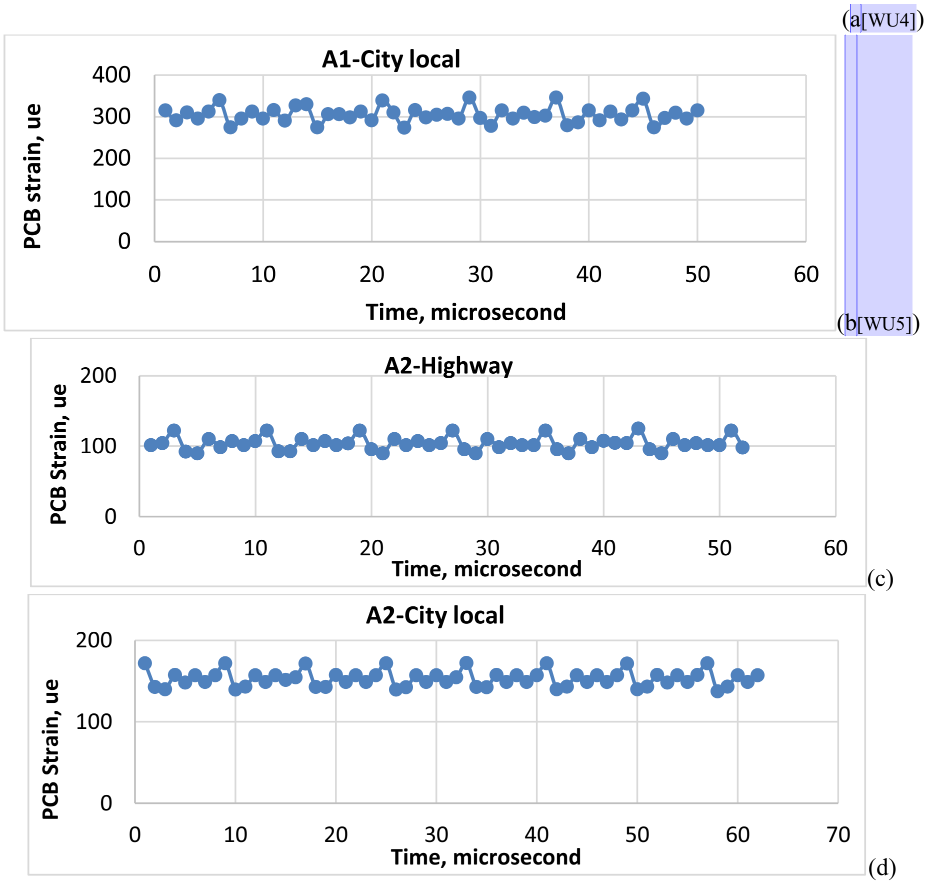


Fig. 8 Example plots of max. Principal PCB strain value in A1 (a and b) and A2 (c and d).

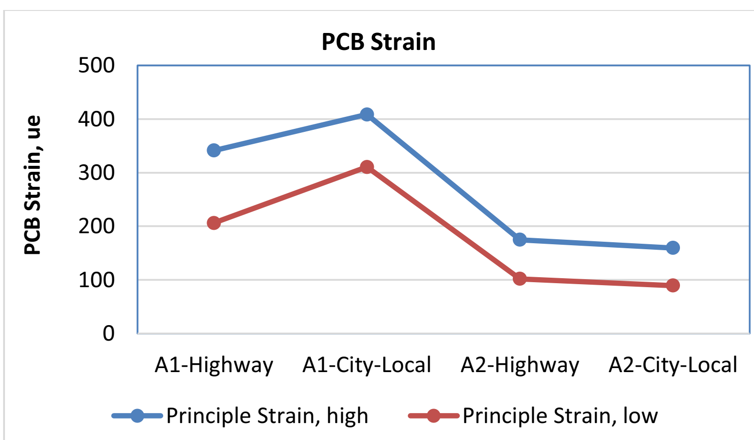


Fig. 9 Max. PCB strain measured from the road test.

IV. CONCLUSIONS

From the limited data collected from road tests in this study, it was observed that the acceleration response is dependent on the type of automobile, driving speed and road conditions. Some other factors such as board and box mounting and position of mounting may also contribute. Automobile A1 may have a higher acceleration and strain which may be due to the sport functionality and board mounting position. The vibration stresses from all cases tested are still in the safety region. However, the severity of the failure risk of the boards is determined not only by the PSD curve but also by the board strain, which is worthy of further studies.

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