

## HVE Vehicle Accelerometers: Validation and Sensitivity

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### ABSTRACT

An understanding of the acceleration experienced at various seating positions in a vehicle is important for predicting occupant dynamics during an event. In most accident reconstructions there may not be an opportunity to instrument the accident vehicle with accelerometers and perform tests at the accident site. Therefore, it is desirable to simulate accelerometers using HVE and when doing so it is important to know that the output data is valid. The output data is highly dependent on the input parameters and an understanding of how the available input parameters affect the output data is important.

This paper compares the results of physical tests and SIMON simulations over two different sizes of flat-top speed bumps at targeted speeds of 10 km/h and 20 km/h. In addition, three different accelerometer positions were used in the physical testing and the SIMON simulations. The vehicle used in both physical and virtual testing was a 2007 Ford Focus SE hatchback. The methods by which the input and output parameters were measured for each condition are described.

Results showed the same characteristic z-axis acceleration pulse in both real and virtual accelerometers, and that associations between them are achievable. For the x and y axes we found that the magnitude of the acceleration was typically below the level of noise from the real-world accelerometer, and therefore no meaningful associations were possible. When considering the test runs in the z-axis with strong-moderate associations, general trends showed good consistency between physical and simulated data for the initial traversing of each axle over the speed bump, and worse consistency for when each axle was near the trailing edge of the speed bump. When considering biomechanical analysis, the simulation should not be used as a sole source for quantifying the magnitude of vibrational acceleration applied to occupants as they travel over speed bumps; however the characteristic pulse shows the general pattern of the applied acceleration. Based on the trends observed in this study, future testing and development should be done before using data from simulated accelerometers that are remote from the CM.

### INTRODUCTION

HVE currently has the capability of simulating up to five accelerometers at one time on a vehicle model. These accelerometers are connected to the sprung mass according to user-entered Cartesian coordinates relative to the sprung mass center of gravity. This paper presents a validation exercise whereby tri-axial accelerometer data collected from the real-world environment was compared to simulation data from HVE vehicle accelerometers.

A paper by Parry et al. (2003) presented a similar study, which compared the results of physical tests and SIMON simulations for five different vehicle types travelling over four different designs of speed bumps, with each vehicle being tested at speeds between 16 to 64 km/h (10 and 40 mph). The study used measured data such as driver's seat vertical acceleration for biomechanical modeling of the human response to repeated travel over speed bumps. Results showed that Centre of Mass (CM) vertical acceleration, wheel vertical displacement and pitch angle/rate showed good consistency between physical and test data.

This paper expands upon research by Parry et al. by focusing on a lower speed range (10 to 20 km/h) for a single vehicle. It also compares the acceleration results at varying accelerometer locations remote from the CM. The results also consider the x and y accelerations in addition to the acceleration in the vertical direction.

Accelerometers were attached near the CM of the vehicle and at two different positions further from the CM. One of these positions was on the outer front passenger seat track of the vehicle, and the other location was at the upper right side latch for the rear seat. By comparing the results of physical tests with the results of simulated tests, the ability of the SIMON model to predict the acceleration values at various locations within a vehicle has been examined.

## METHODOLOGY

The vehicle testing was conducted on two different flat-top speed bumps on a roadway in a public park. Figures 1 to 3 present the speed bumps and their approximate dimensions. The vehicle's direction of travel in the figures is from the right side to the left. The HVE 3D Environment models were created using a Total-Station survey of the speed bumps.



Figure 1. Photograph of the Small Flat-top Speed Bump.

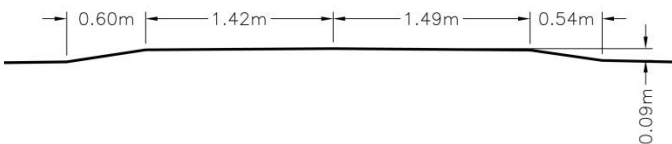


Figure 2. Approximate Dimensions of the Small Flat-top Speed Bump

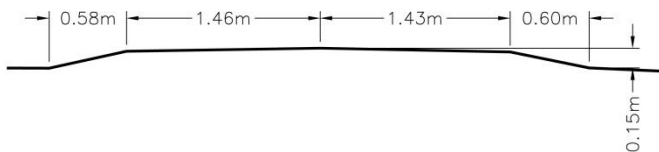


Figure 3. Approximate Dimensions of the Large Flat-top Speed Bump

The test vehicle was a 4-door 2007 Ford Focus SE, with an odometer reading of approximately 200,000 km. It was instrumented with a tri-axial accelerometer and driven over both speed bumps five times at a targeted speed of 10 km/h, and then the small speed bump five times at 20 km/h. This was then repeated for each of three accelerometer mounting positions. The sign convention (Figure 4) was positive x,y,z represents forward, rightward and upward with respect to the vehicle, and the HVE z-axis (positive is downward, SAE) polarity was reversed for consistency.

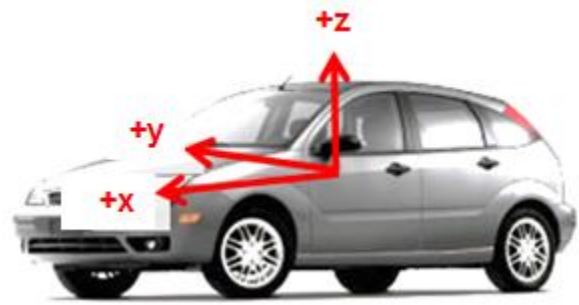


Figure 4. Sign Convention.

The "CM" accelerometer mounting position (Location 1) needed to be a hard metal spot, as close to the CM as possible, without compromising the vehicle. Therefore the right front passenger's seat-track, at the front on the left side was used. Considering the CM of the vehicle to be x,y,z = (0,0,0), the Cartesian coordinate of this position was (-0.02,+0.13, -0.17 m). The "Lateral" accelerometer mounting position (Location 2) was chosen as the right front passenger's seat track on the right side, (-0.02, +0.58, -0.17 m). The "Right, Rearward, and High (RRH)" accelerometer position (Location 3) was chosen as the right upper rear seat mount, (-1.52, +0.64, +0.49 m), which would be near the right shoulder of an occupant seated in the right rear. The positions of the accelerometers in the HVE vehicle matched these positions.

The accelerometer was a Pendant G Acceleration Data Logger by MicroDAQ Ltd. It had a measurement range of +/- 3 g and a resolution of 0.025 g. The logging interval was set to 100 Hz (0.01 seconds). To establish an accurate vehicle speed at 10 km/h and 20 km/h, pedal blocks were used along with GPS speed data.

## HVE SIMULATIONS

The SIMON simulations involved a 2000-2011 4-door Ford Focus SE test vehicle traversing the two different speed bumps. Two occupants were seated in the vehicle, one driver and one right rear passenger, matching the weight of the occupants that were in the test vehicle during the physical tests. The vehicle was started approximately 10 m back from the speed bump, the initial speed was set to 10 km/h or 20 km/h depending on the condition, and the accelerator pedal was set at a steady state to maintain vehicle speed. There was no steering or braking input. HVE accelerometers were placed in the same position as the real-world accelerometers. Output variables included x, y, and z axes acceleration for the 3 accelerometer locations. The output time interval was set to 100 Hz to match the logging interval of the physical accelerometer in the real-world tests.

## DATA ANALYSIS

The independent variables for the study were the targeted speed of the vehicle (10 km/h or 20 km/h); the height of the speed bump (small or large); the accelerometer location

(Location 1 = CM, Location 2 = Lateral, and Location 3 = RRH); and finally the condition of being simulated or a physical test. The dependent variables for the study were the acceleration in the x, y, and z axes.

The physical accelerometer data was processed using a Butterworth filter, per SAE J211 standards. Next, the physical and simulated acceleration data was plotted on the same graph for each test condition. A 5-point moving average was used to smooth the physical accelerometer data. The statistical agreement between the physical test data and the simulation data for each condition was examined by comparing the plots, and also by using a Pearson's Correlation Coefficient. This statistical procedure provides an indication of the strength and direction of the relationship between two sets of data. The results of these analyses are summarized in Table 1. This procedure yields a single number that ranges between -1.00 and +1.00. The closer the absolute value is to 1.00, the stronger the relationship. The closer the absolute value is to 0.00 the weaker the relationship. A value of +1.00 signifies a perfect positive relationship, while a value of -1.00 indicates a perfect inverse relationship. The sign does not affect the strength of association; rather it simply indicates the direction in which the variables change in relation to each other.

The following ranges can be used as a general guide to the strength of correlation between two sets of data as defined by the absolute value of the correlation coefficient:

Table 1. Pearson's Correlation Coefficient – General Guideline

Pearson's Correlation Coefficient	Association
0.80-1.00	Strong Association
0.60-0.79	Strong-Moderate Association
0.40-0.59	Moderate Association
0.30-0.39	Moderate-Weak Association
0.20-0.29	Weak Association
0.00-0.19	Little, if any association

## RESULTS

The x, y, and z-axis acceleration was collected for the various test conditions in the simulated and real-world environment. A characteristic acceleration pulse resulted in the z-axis from traversing either speed bump, regardless if it was extracted from the real or virtual accelerometer. A typical z-axis acceleration pulse is shown in Figure 5. The pulse contains 8 key events which are detailed in Table 2 next to the approximate time in the HVE simulation. It should be noted that events 1 to 4 in Table 2 coincide with the acceleration peaks, but for events 5 to 8, there was some natural lag between the moment of the event (i.e. the Table 2 value) and the acceleration peak.

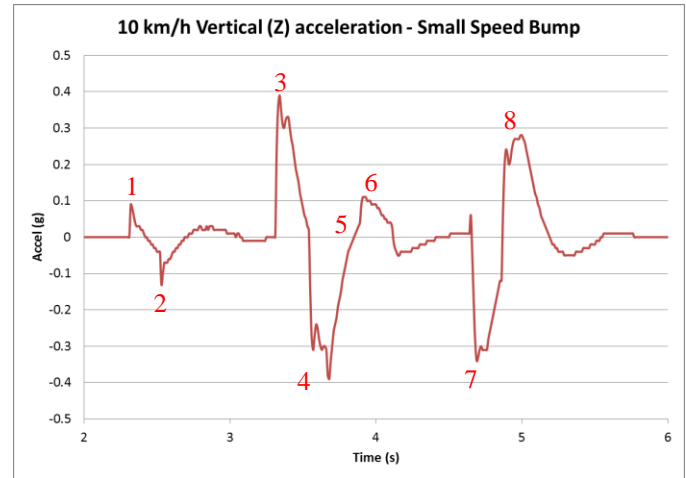


Figure 5. Characteristic Z-axis Acceleration Pulse, showing Events 1 to 8

Table 2. Events in Acceleration Pulse from a Characteristic Speed Bump

Event	HVE Time (s), approximate		
	10 km/h Small Bump	10 km/h Large Bump	20 km/h Small Bump
1 Front Wheel at Bottom of Bump Leading Edge	2.3	2.1	1.1
2 Front Wheel at Top of Bump Leading Edge	2.5	2.4	1.3
3 Rear Wheel at Bottom of Bump Leading Edge	3.3	3.2	1.6
4 Rear Wheel at Top of Bump Leading Edge	3.5	3.5	1.75
5 Front Wheel at Top of Bump Trailing Edge	3.7	3.6	1.8
6 Front Wheel at Bottom of Bump Trailing Edge	3.9	3.9	1.95
7 Rear Wheel at Top of Bump Trailing Edge	4.7	4.6	2.25
8 Rear Wheel at Bottom of Bump Trailing Edge	4.9	4.9	2.4

Appendix A presents comparison plots between the real and simulated tests for z-axis acceleration. In the plots, the red line represents the HVE data, the faint grey line represents the Butterworth filtered accelerometer data, and the blue line represents the 5-point moving average. Two plots for each condition are presented: the "best" and the "worst" (i.e. the plots with the strongest and weakest association). The Pearson's Correlation Coefficients for the z-axes are presented in Table 3. The test runs with strong-moderate Pearson coefficients (i.e. 0.6 and above) are highlighted.

Table 3. Pearson Correlation Coefficients for z-axis Conditions

	Location 1 = Near CM				
	Run a	Run b	Run c	Run d	Run e
10 km/h, Small Bump	-0.12	0.33	0.63	0.23	0.39
10 km/h, Large Bump	0.72	0.11	0.31	0.10	0.43
20 km/h, Small Bump	0.23	0.27	0.74	0.80	0.84
	Location # 2 = Lateral				
	Run a	Run b	Run c	Run d	Run e
10 km/h, Small Bump	-0.05	0.49	0.72	0.82	0.78
10 km/h, Large Bump	-0.21	0.83	0.80	0.22	0.82
20 km/h, Small Bump	0.76				
	Location # 3 = Rear Right High				
	Run a	Run b	Run c	Run d	Run e
10 km/h, Small Bump	0.31	0.17	0.60	0.17	0.14
10 km/h, Large Bump	0.33	0.24	0.69	0.12	0.34
20 km/h, Small Bump	0.35	0.25	0.32	0.56	0.42

Results in Table 3 above show that when comparing the physical and simulated data, there were several test runs with strong-moderate associations (i.e. Pearson coefficients  $\geq 0.6$ ). However there were many tests that were only moderately associated or worse.

Although the targeted speed was very close to the 10 and 20 km/h condition before and after traversing the speed bump, it was observed that the vehicle speed fluctuated when climbing and descending the speed bump in both the real and the simulated HVE environment. In an attempt to better control the speed of the physical test vehicle, numerous designs of pedal blocks were experimented with to control the targeted speed more accurately, however at these low speeds even a small degree of acceleration pedal adjustment affected the period of the acceleration pulse. Figure 6 depicts a sample comparison plot where the test vehicle (blue line) took less time to traverse the speed bump than the HVE model (red line).

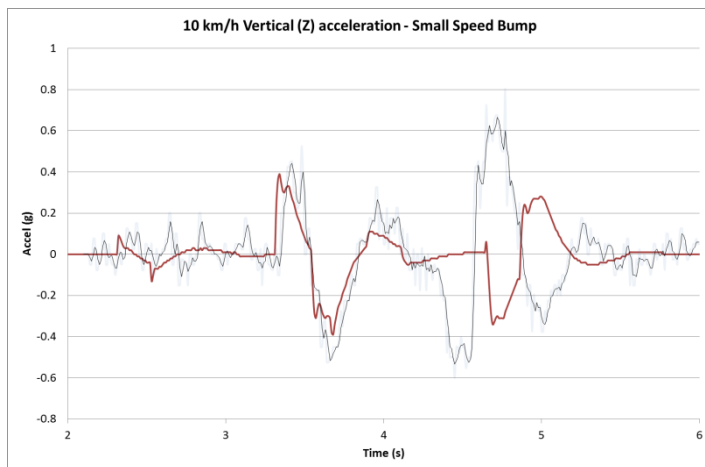


Figure 6. Poor Period Alignment due to Vehicle Test Speed

We see in Figure 6 that although both the simulated and physical data shows the characteristic acceleration pulse, the overall period of the pulse does not match, and the various peaks and valleys get proportionally out of phase as time increases.

Calculations of the average vehicle speed between event 1 and 8 were performed for each test run, and we found several instances where an overall inaccurate test vehicle speed (error  $\geq 10\%$ ) was consistent with a low Pearson coefficient. Furthermore, when performing calculations of the average vehicle speed between events at the beginning, middle, and end of the acceleration pulse, we found several instances where a high variation in speed ( $\geq 5$  km/h) was consistent with a low Pearson coefficient. These calculations however did not always show a proportional relationship to the Pearson coefficient, and there are likely several other contributing factors which could cause poor associations. The combination of speed inaccuracy and variation might also have been an influence.

Appendix B presents comparison plots between the real and simulated tests for the x and y axes. Although this data could be used to calculate an overall Root Mean Square (RMS) result for the combined x, y, and z axes, we found that the magnitude of the acceleration in the x and y axes were typically below 0.2 g, and therefore the noise from the real-world accelerometer contributed more to the signal than any meaningful data. For the y direction, a very low or zero acceleration was expected since the vehicle was traversing the speed bump at 90 degrees and there would be no acceleration input in the lateral (y) direction. Pearson values for x and y were below 0.6 and therefore we did not analyze the differences in test conditions.

## DISCUSSION

For the analysis of the differences in test conditions, only the test runs with strong-moderate associations (i.e. Pearson coefficients  $\geq 0.6$ ) were studied (although for Location 3 at 20 km/h, test run d was used because it was the highest reported correlation (0.56) of all the runs). Figure 7 presents a comparison of field and simulated acceleration, considering the average absolute value of the peak values associated with the 8 acceleration events in the acceleration pulse (events are described above in Table 2).

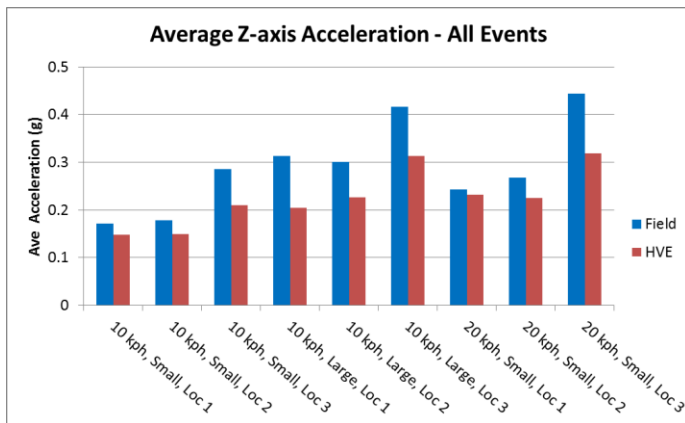


Figure 7. Average Z-axis Acceleration of all Events in the Acceleration Pulse

Figure 7 shows that the average accelerations for the small speed bump were approximately 65% of the large speed bump, and the average accelerations at 10 km/h were approximately 67% of the acceleration at 20 km/h. When considering the differences between the accelerometer positions, the average acceleration tended to be similar at the CM and Lateral position (especially for the small speed bump), which is expected since only the y-axis position of the accelerometer changes, and the vehicle traverses the speed bump at a 90 degree approach angle. However, the acceleration was larger for the RRH position - the average accelerations at the CM and Lateral positions were approximately 63% of the accelerations observed at the RRH position.

When comparing real vs. simulated accelerometers at 10 km/h and 20 km/h for the small speed bump, the real accelerometer had approximately the same magnitude of acceleration as the virtual accelerometer in the CM and Lateral positions; however the real accelerometer read approximately 36 to 39% higher than the simulated accelerometer in the RRH position. For the large speed bump, the real accelerometer read approximately 40% higher than the simulated accelerometer. When examining data to explain these differences, we found that the events in the acceleration pulse with the most consistency between real and simulated values were typically the peak values near #1 and #3 (i.e. the positions towards the start of the pulse, where the front and rear wheels are at the bottom of the leading edge of the speed bump). The events in the acceleration pulse with the most discrepancy between real and simulated values were typically the peak values near #6 and #8 (i.e. the positions towards the end of the pulse, where the front and then the rear wheels are at the bottom of the trailing edge of the speed). Figures 8 to 11 present the acceleration comparison between real and simulated data for these positions.

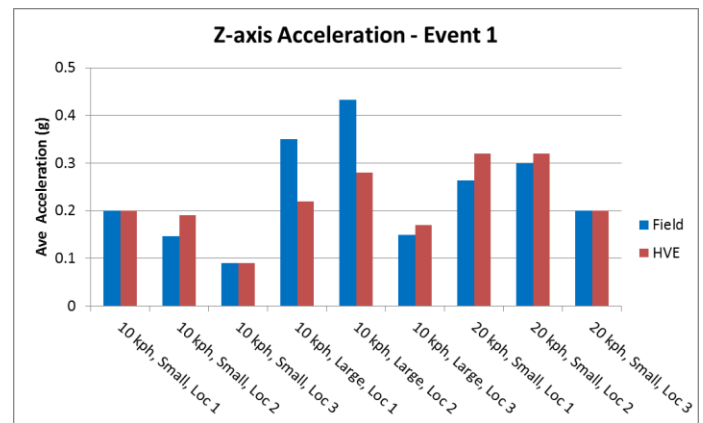


Figure 8. Acceleration Comparison at Event 1 of the Acceleration Pulse – Front Wheels at the Leading Edge of the Speed Bump

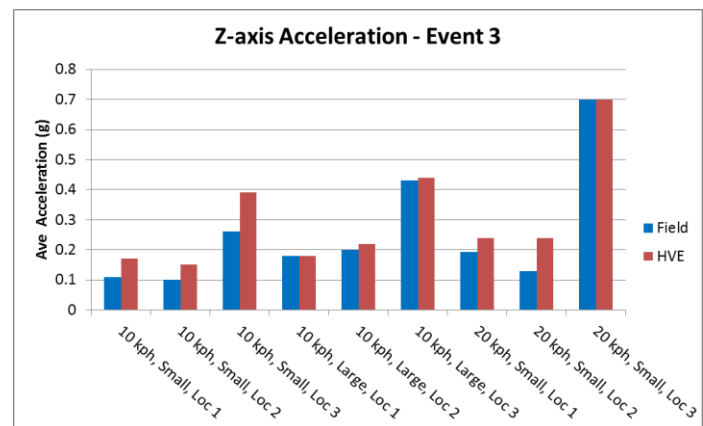


Figure 9. Acceleration Comparison at Event 1 of the Acceleration Pulse – Rear Wheels at the Leading Edge of the Speed Bump

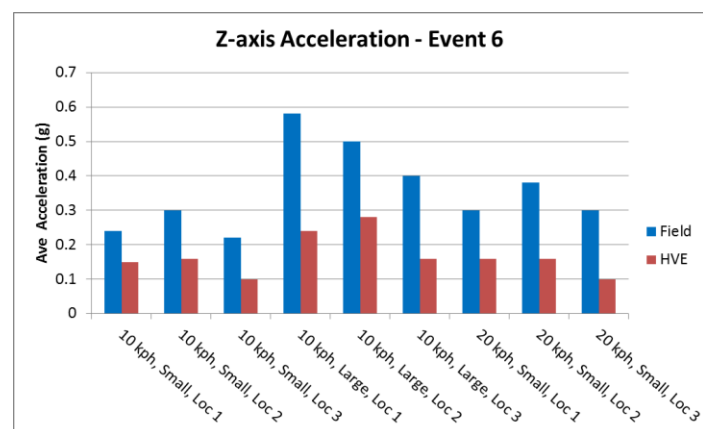


Figure 10. Acceleration Comparison at Event 6 of the Acceleration Pulse – Front Wheels Just Past the Top of the Trailing Edge of the Speed Bump



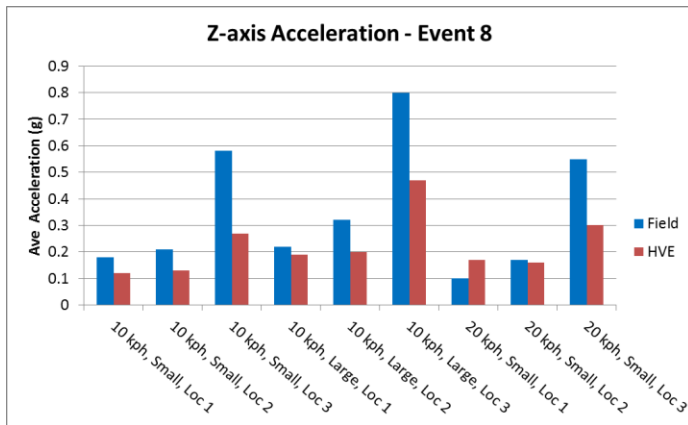


Figure 11. Acceleration Comparison at Event 8 of the Acceleration Pulse – Rear Wheels Just Past the Top of the Trailing Edge of the Speed Bump

In Figure 8, the average accelerations generally matched between the field and the simulation; however for the 10 km/h large speed bump the field acceleration was larger than HVE acceleration for Location 1 and 2. In Figure 9, the average accelerations generally matched between the field and the simulation; however for the 10 km/h small speed bump the HVE acceleration was larger than the field acceleration at location 3.

In Figure 10, the field data is larger than HVE data specifically at Event 6 in the acceleration pulse. One possibility for this may be related to the compounding effects of the front and rear suspension of the vehicle as it traverses over the speed bump. Figure 11 shows the tendency of the field data to be significantly larger at the RRH position. This result indicates a trend of HVE accelerometers to under-predict in positions that are higher and closer to the sides of the vehicle.

The HVE vehicle model was also adjusted by using the radial spring model for the tires. Although results showed a very slight reduction in the acceleration peaks ( $\leq 0.05g$ ), this was not enough to make a difference compared to the noise of the acceleration signals. To be sure that the difference was minimal, we compared the HVE signals with and without the radial spring applied, and found the following Pearson coefficients to be 0.97 to 0.99, indicating almost perfect association. The very strong correlation between the SIMON simulation, with-and-without the radial spring model, confirms that it does not make much difference for this low-level acceleration scenario. This makes sense since the radial spring model is typically used for tire impacts that have a more severe obstacle than a speed bump.

The data shows very low ( $<0.1g$ ) acceleration in the y direction, which is expected since the vehicle was traversing the speed bump at 90 degrees and there would be no acceleration input in the lateral (y) direction. The only slight lateral input could be if the speed bump is not traversed at precisely 90 degrees.

The error in the simulated accelerometer results was also likely due in part to error in the simulated CM motion. The source of this error would be the difference between simulated vs. actual

suspension, tire properties, and the test weight (e.g. the amount of fuel in the tank would affect the test weight). Also, the accuracy of accelerometer location presents another potential source of error, since it is difficult to measure the position of the real accelerometer to much more accuracy than  $\pm 1$  inch due to the physical size of the casing. Care should be taken to locate the simulated accelerometers about the Total Mass CM (not Sprung Mass CM) if the position of the actual accelerometers were measured about the Total Mass CM of the actual vehicle. In the case of the 2007 Ford Focus, the difference between the Sprung Mass CM and Total Mass CM location was less than 1 inch in the x and z axes, with resulting differences in acceleration of 0.01 g or less for traversing the speed bump.

## CONCLUSIONS

Results showed the same characteristic z-axis acceleration pulse in both real and virtual accelerometers, and that associations between them are achievable. For the x and y axes we found that the magnitude of the acceleration was typically below the level of noise from the real-world accelerometer, and therefore no meaningful associations were possible. When considering z-axis test runs with strong-moderate associations (i.e. Pearson coefficients  $\geq 0.6$ ), general trends showed good consistency between physical and simulated data for the initial traversing of each axle over the speed bump (i.e. events 1 and 3), and worse consistency for when each axle was rebounding after the initial compression stage just past the top of the trailing edge of the speed bump. The real accelerometer tended to have slightly higher peaks toward the end of the pulse. These higher peaks at the end of the pulse for the real accelerometer were especially noted when considering the large speed bump at 10 km/h. When considering the differences between the accelerometer positions, the real accelerometer tended to have approximately the same magnitude of acceleration as the virtual accelerometer in the CM and lateral positions; however the real accelerometer read approximately 36 to 39% higher in the RRH position. The radial spring model for the tires had almost no effect (Pearson coefficients 0.97 to 0.99) on the simulated vs. real differences for this low-level acceleration scenario.

A biomechanical analysis considers vehicle dynamics before predicting occupant kinematics. This study shows that traversing a speed bump at 10 to 20 km/h would present a complex acceleration pulse to occupants, with 8 events over a short period of time. Since there is not one specific peak value but rather many values, this event would likely be considered a vibration and not an impact. Since the results of this study showed many cases of low consistency between simulated and real accelerometer data, a simulation should not be used as a sole source for quantifying the magnitude of vibrational acceleration applied to occupants as they travel over speed bumps; however the characteristic pulse would show the general pattern of the applied acceleration. Since the most accurate acceleration values were at the beginning of the event and the compounding acceleration signal becomes increasingly difficult to simulate as time progresses, care should be taken to use the values at the beginning of a compounding vibration and not at the end. Based on the trends observed in this study, future testing and development

should be done before using data from simulated accelerometers that are remote from the CM.

## **FUTURE TESTING**

Future testing methodology should involve a more precise way to match vehicle speed between physical and virtual tests. The best method for this would be to pick a precise targeted speed and use an electronic way of controlling the accelerator pedal of the physical test vehicle. The percent WOT (Wide Open Throttle) could be collected directly from the test vehicle used as an input for the HVE driver throttle table. To ensure this method is accurate, validation studies would have to be done for the %WOT and gearing of the physical and simulated vehicle. Another method to consider would be to measure the precise vehicle speed as it traverses the speed bump and perform several iterations of HVE in order to match the vehicle speed; however this method would introduce some degree of hand-approximation of HVE inputs to make vehicle test speeds match.

The trends in the results for this study should be qualified by increasing the number of physical test runs so that statistically significant results can be achieved. The effect of the location of the accelerometer position remote from the CM should be studied further with more tests at more remote locations to verify if underreporting is a trend as you move away from the CM along axes that are not lateral to the acceleration pulse. Future testing should also be done with three accelerometers at once in the physical test vehicle so that the exact same input could be compared between the accelerometer positions. Future testing should involve studying an acceleration pulse which includes some degree of lateral y-axis input, such as a study of the sensitivity of hitting the speed bump at various approach angles that are not purely 90 degrees. Future tests could also involve instrumenting the vehicle with a higher quality accelerometer to study very low level accelerations.

## **CONTACT**

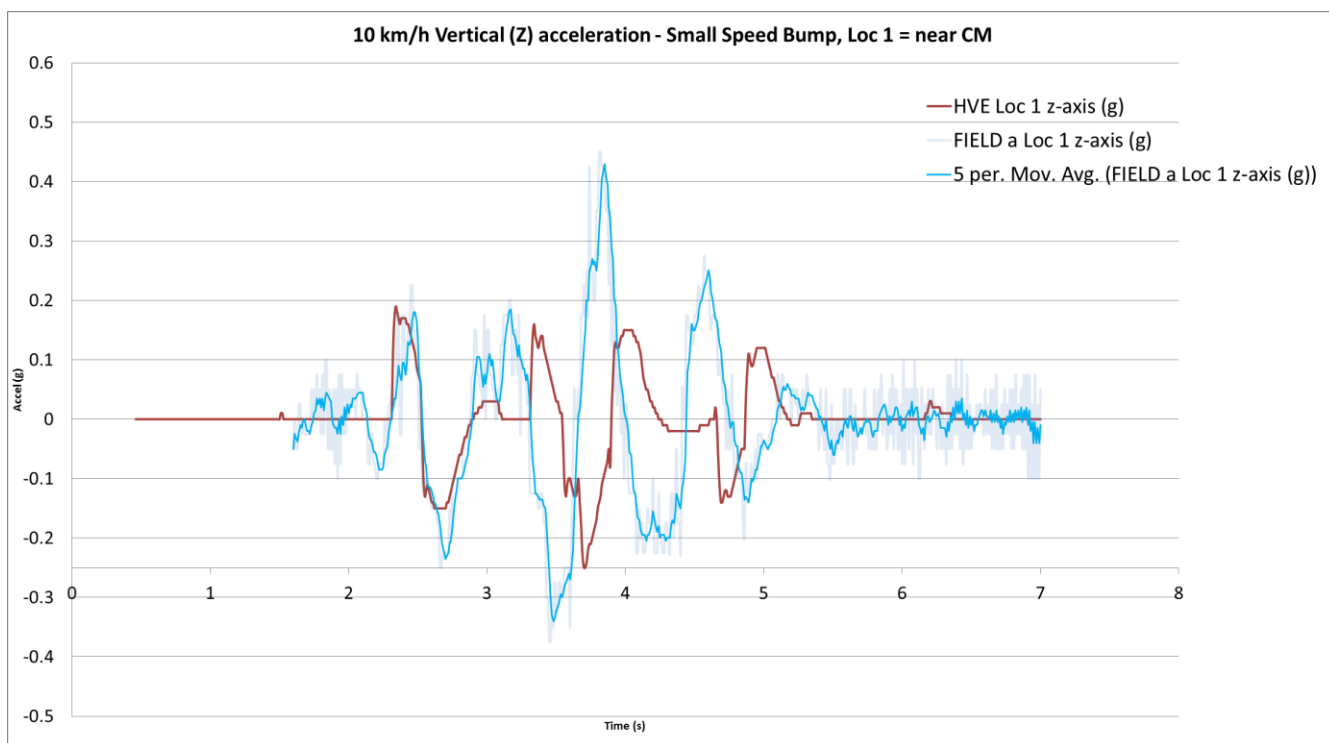
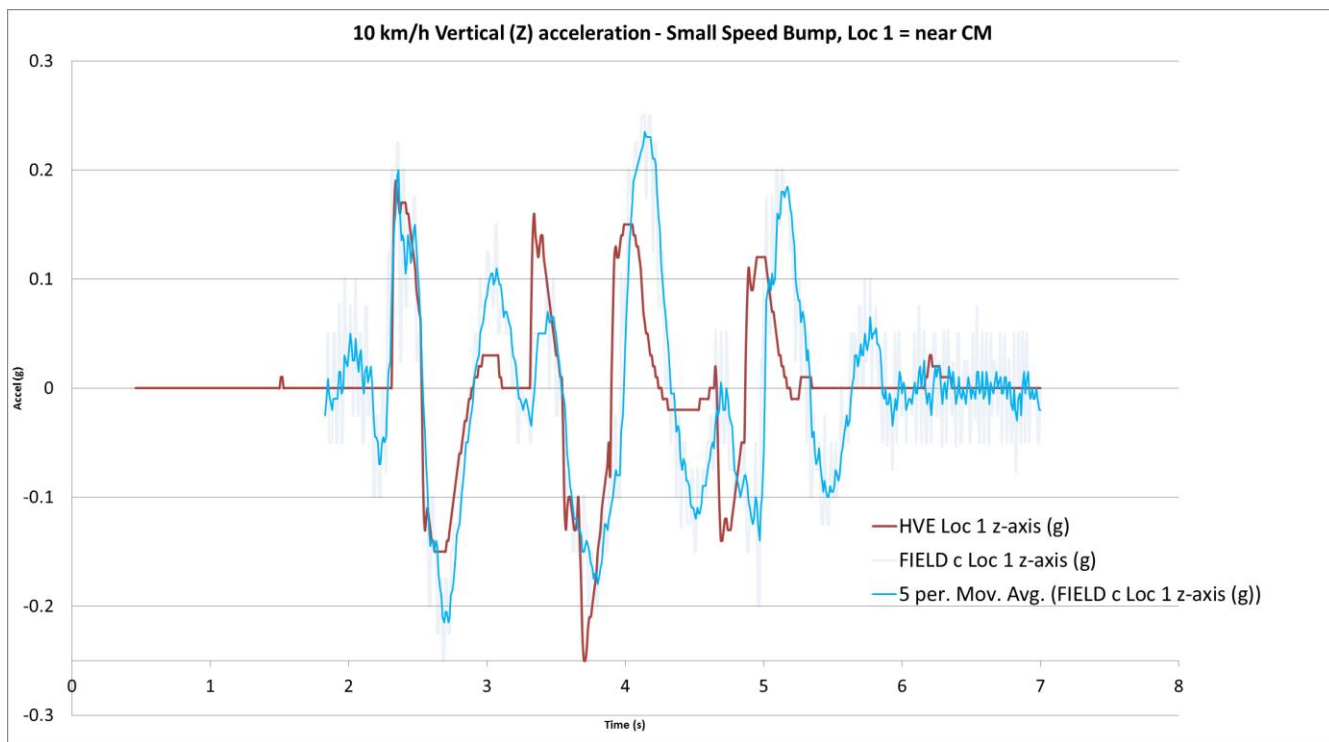
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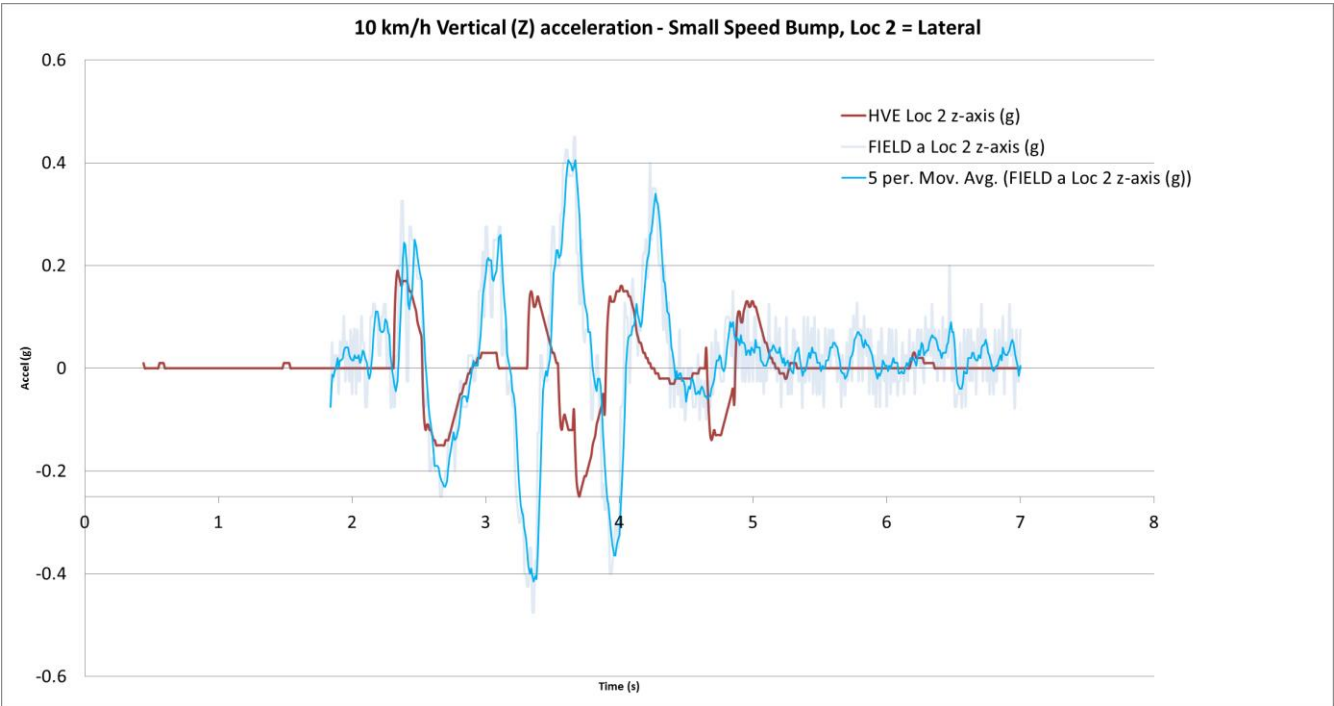
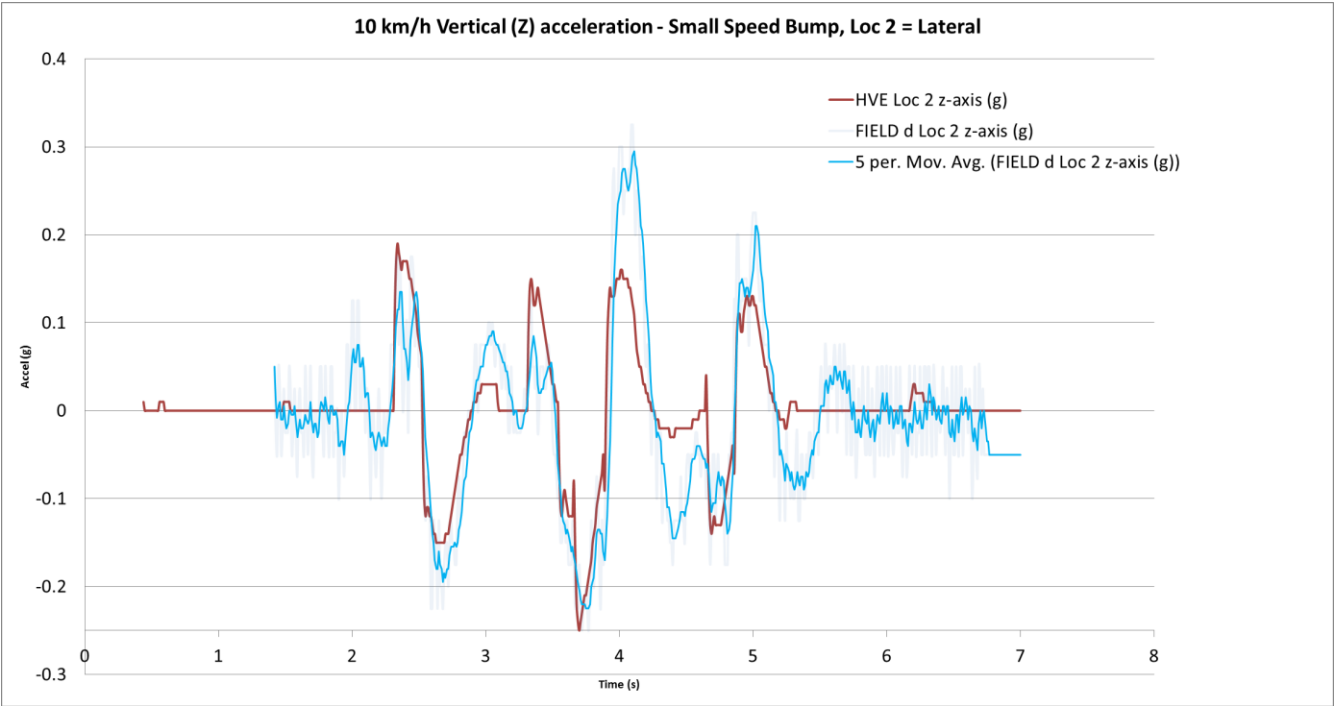
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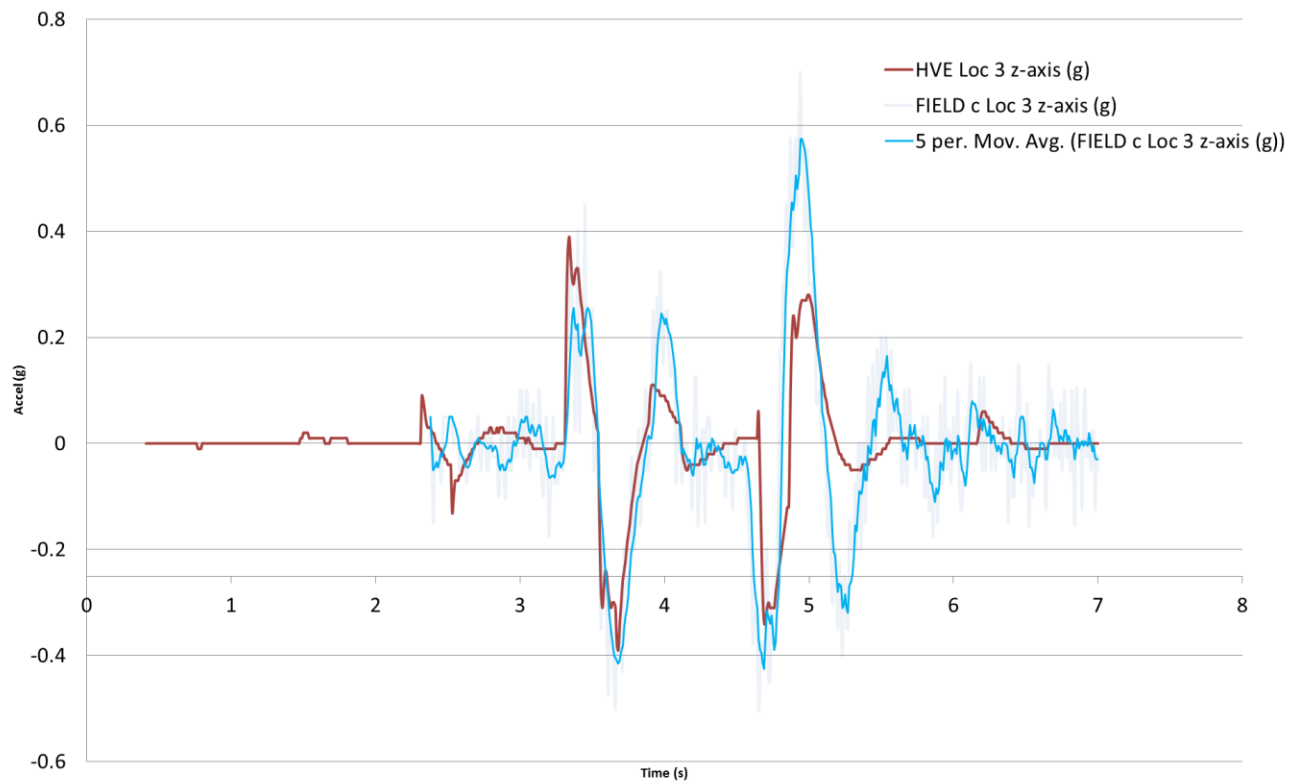
## **APPENDIX A – ACCELERATION COMPARISON PLOTS: Z-AXIS**



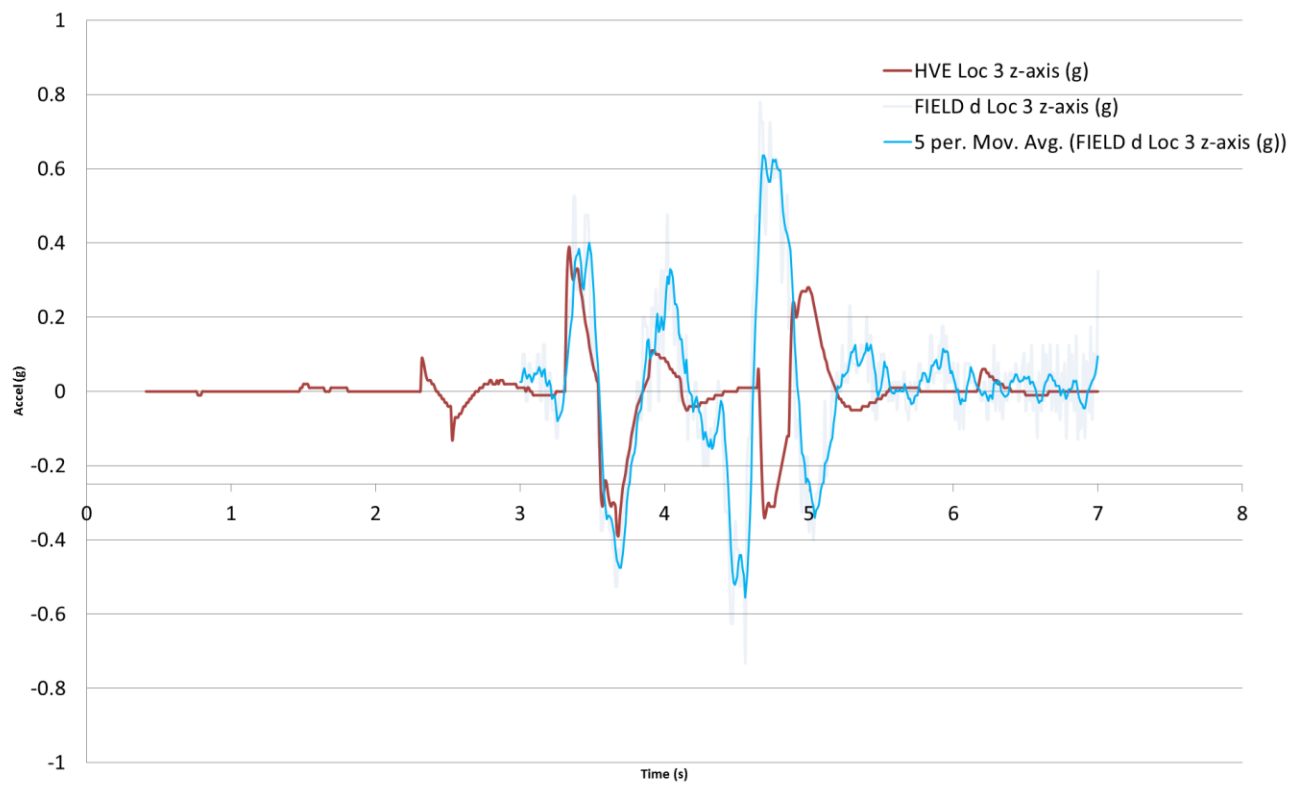


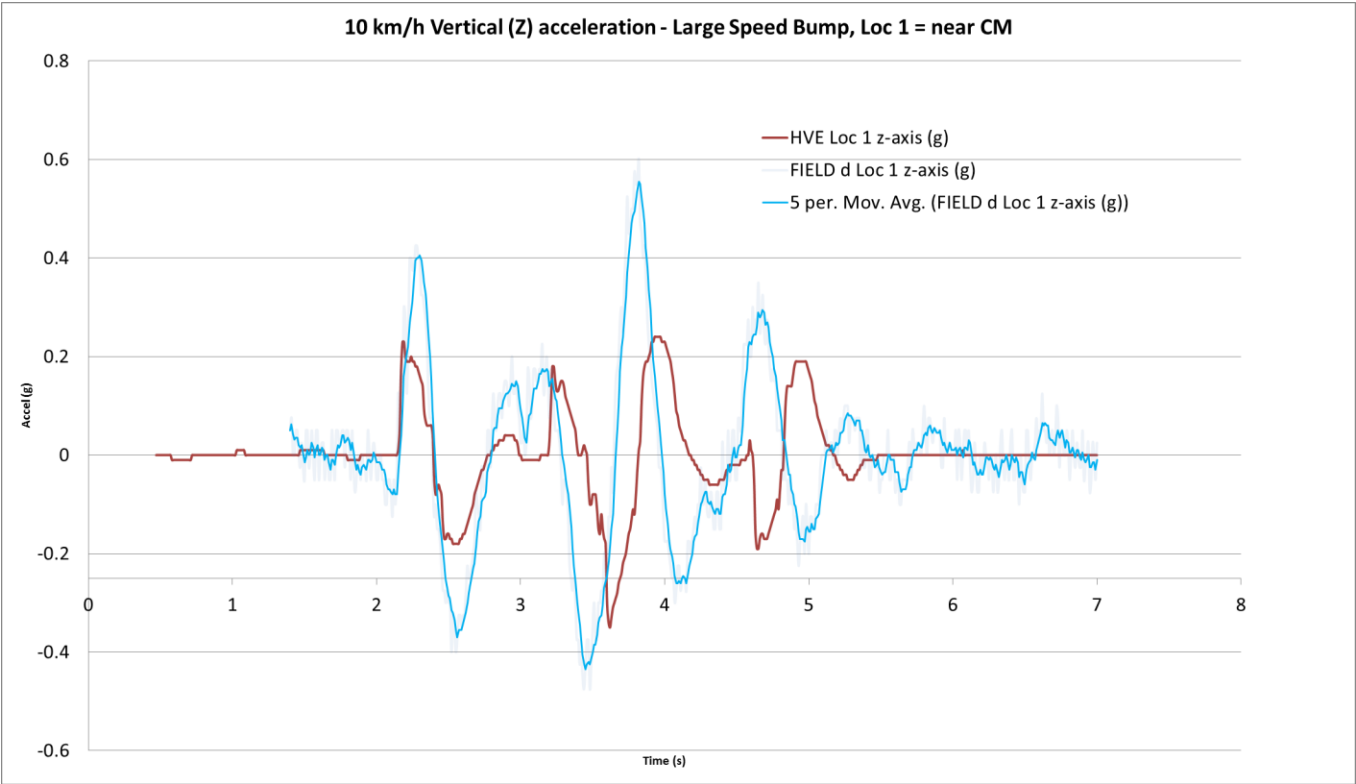
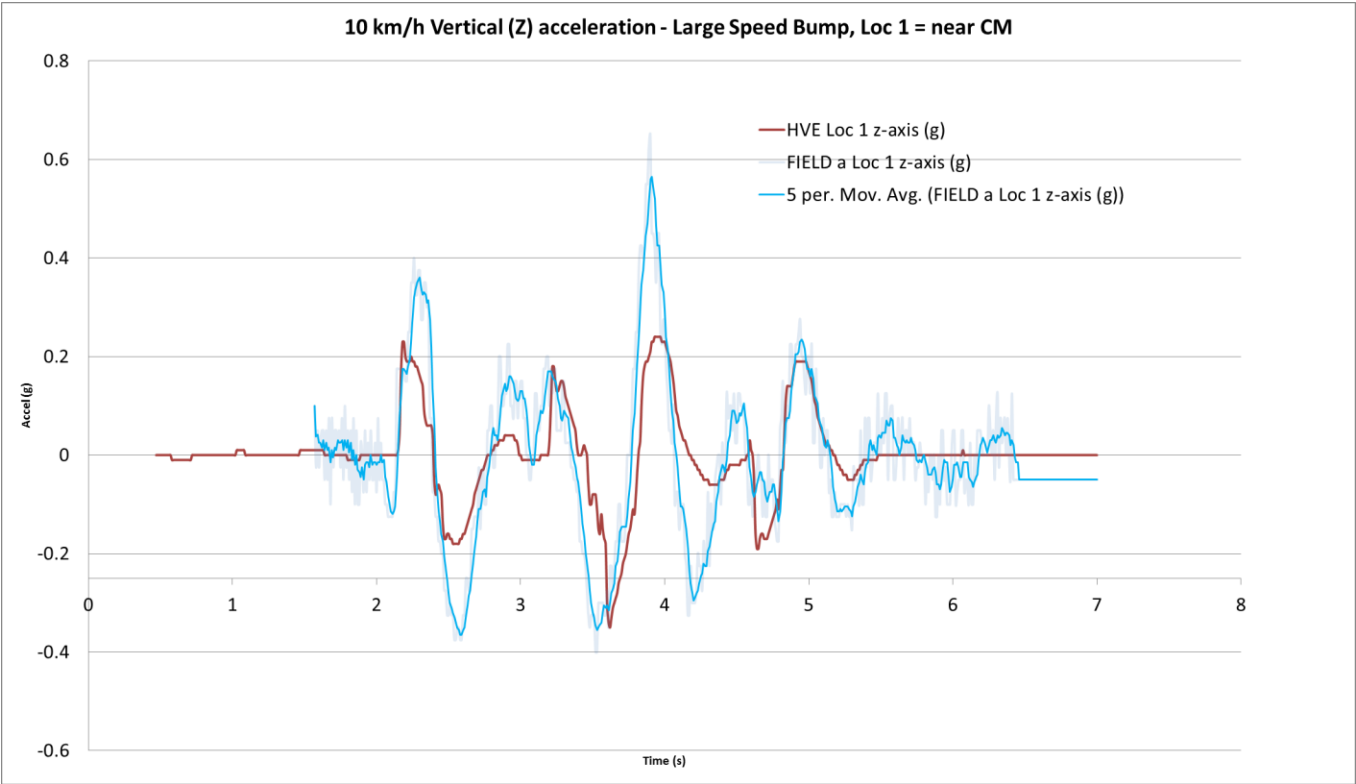


10 km/h Vertical (Z) acceleration - Small Speed Bump, Loc 3 = RRH

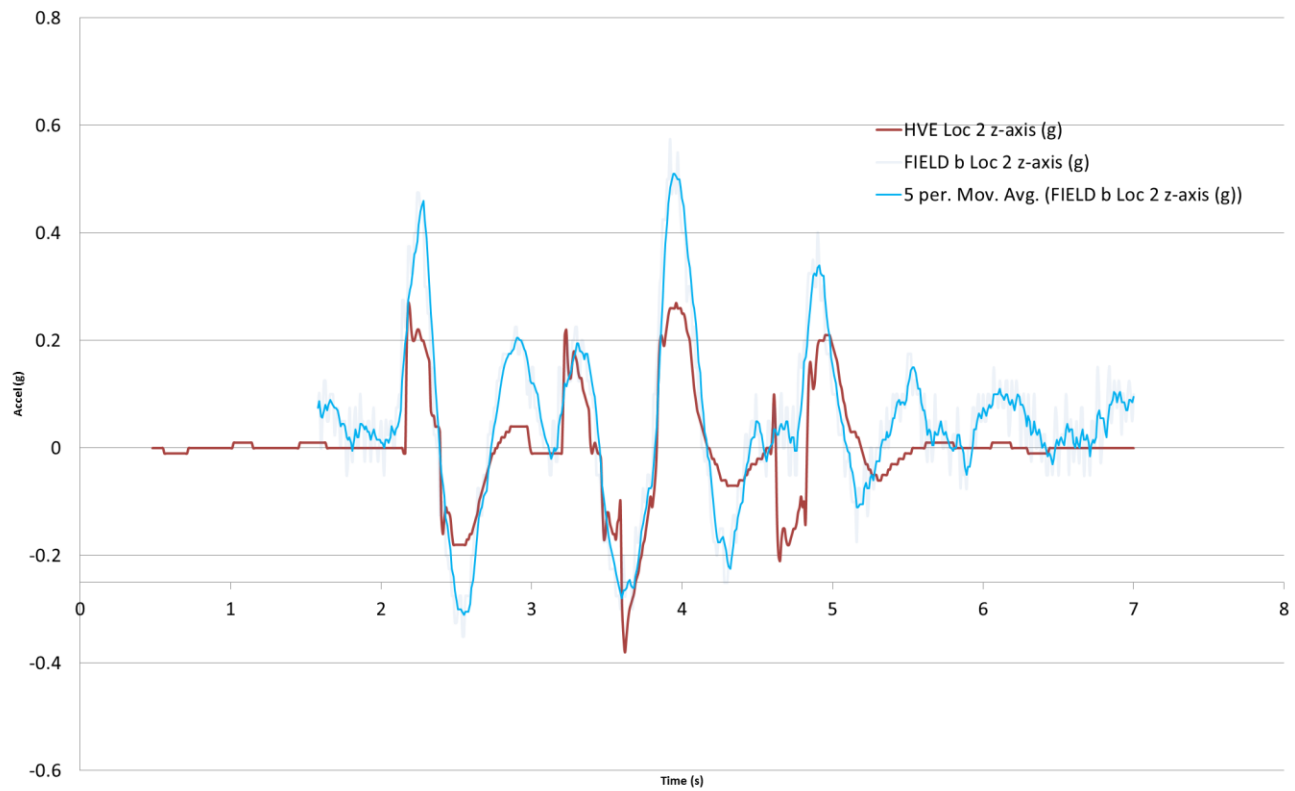


10 km/h Vertical (Z) acceleration - Small Speed Bump, Loc 3 = RRH

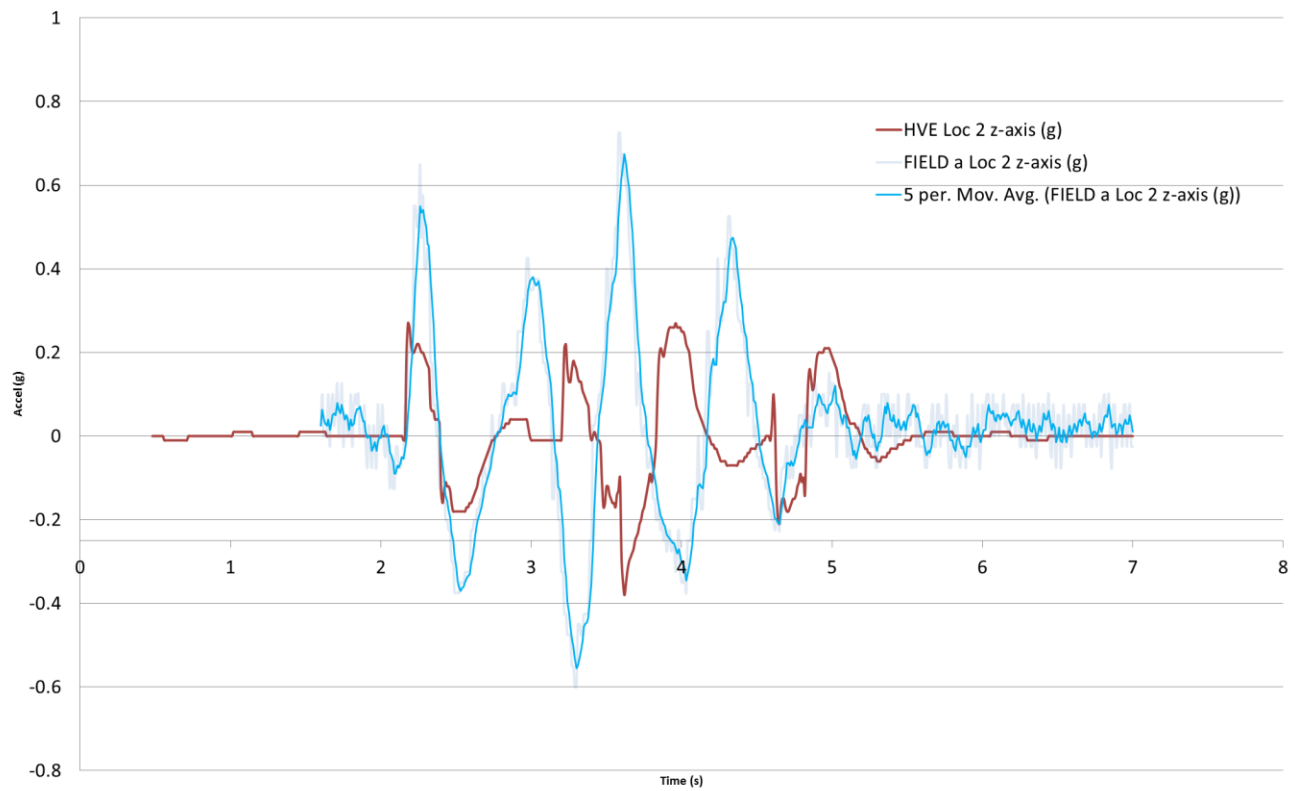




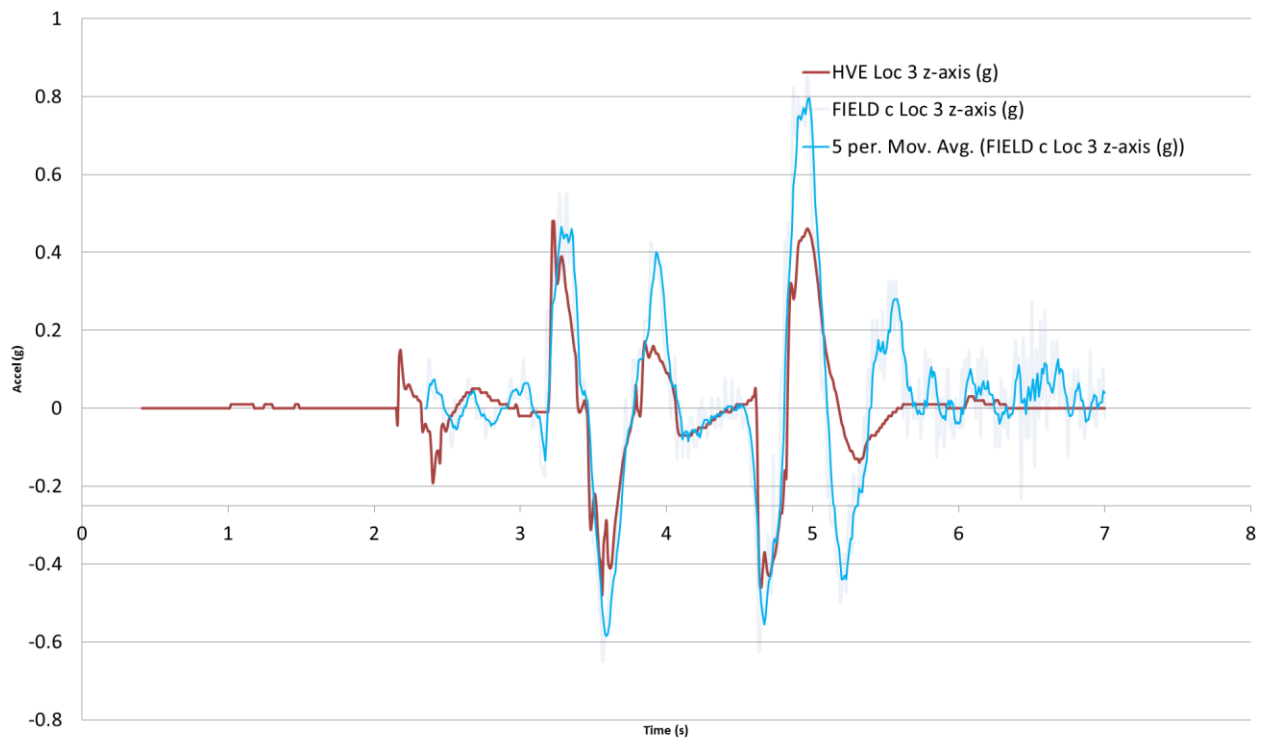
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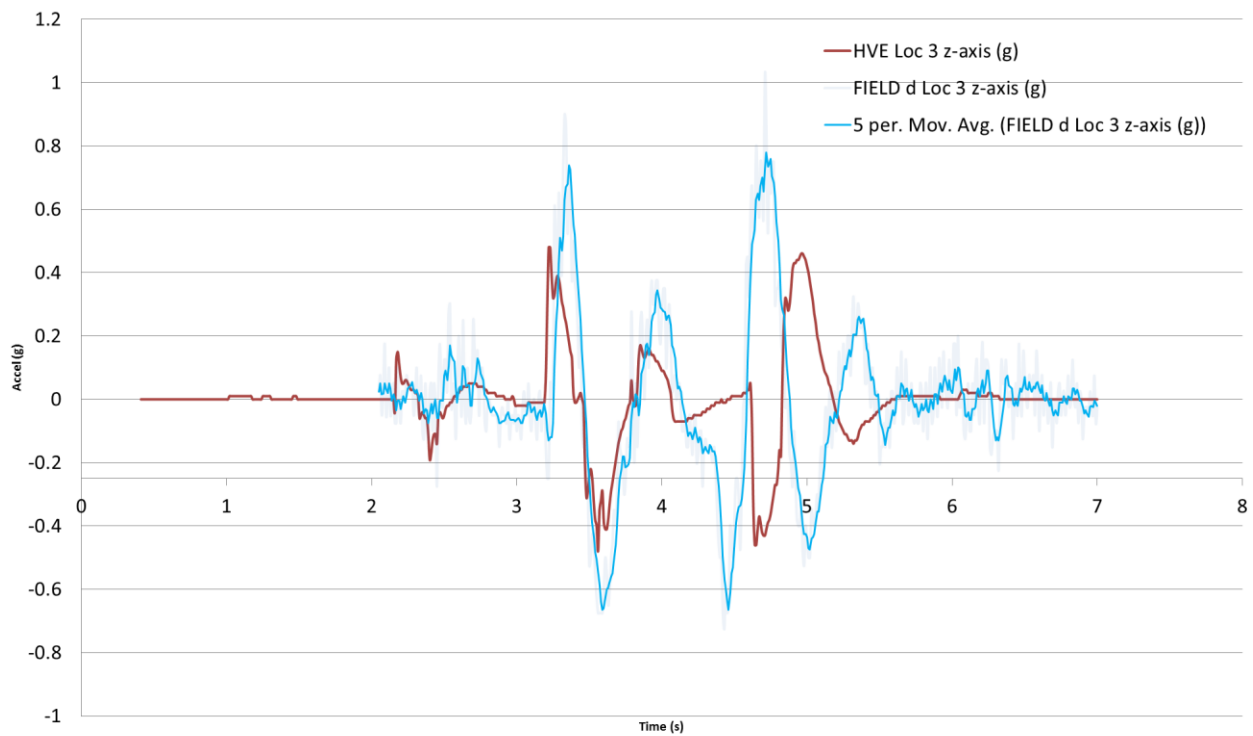
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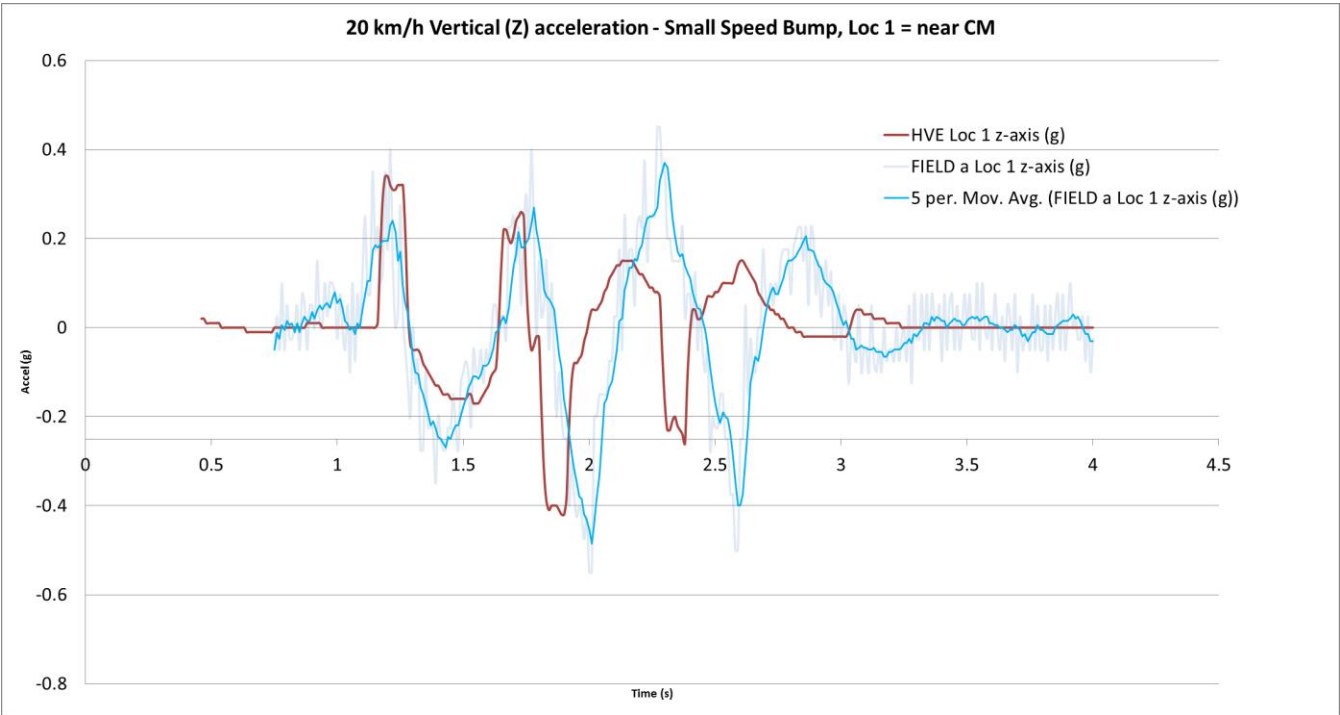
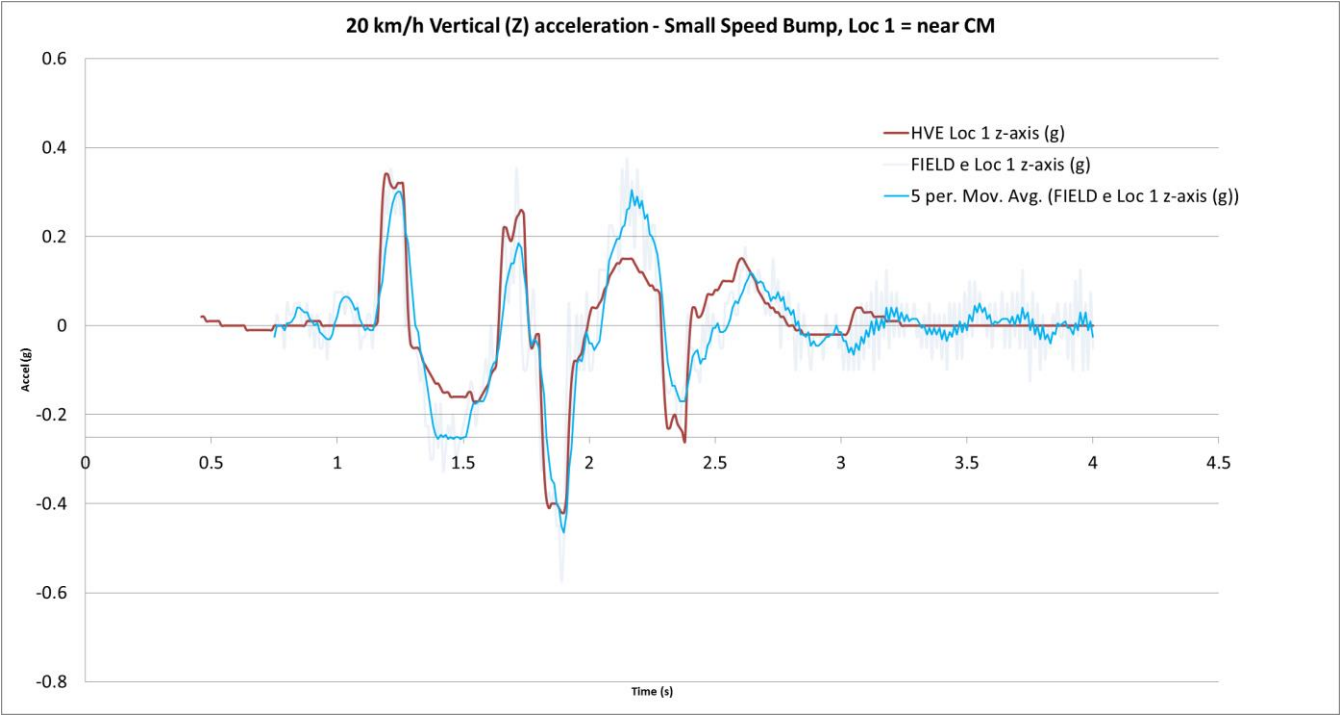
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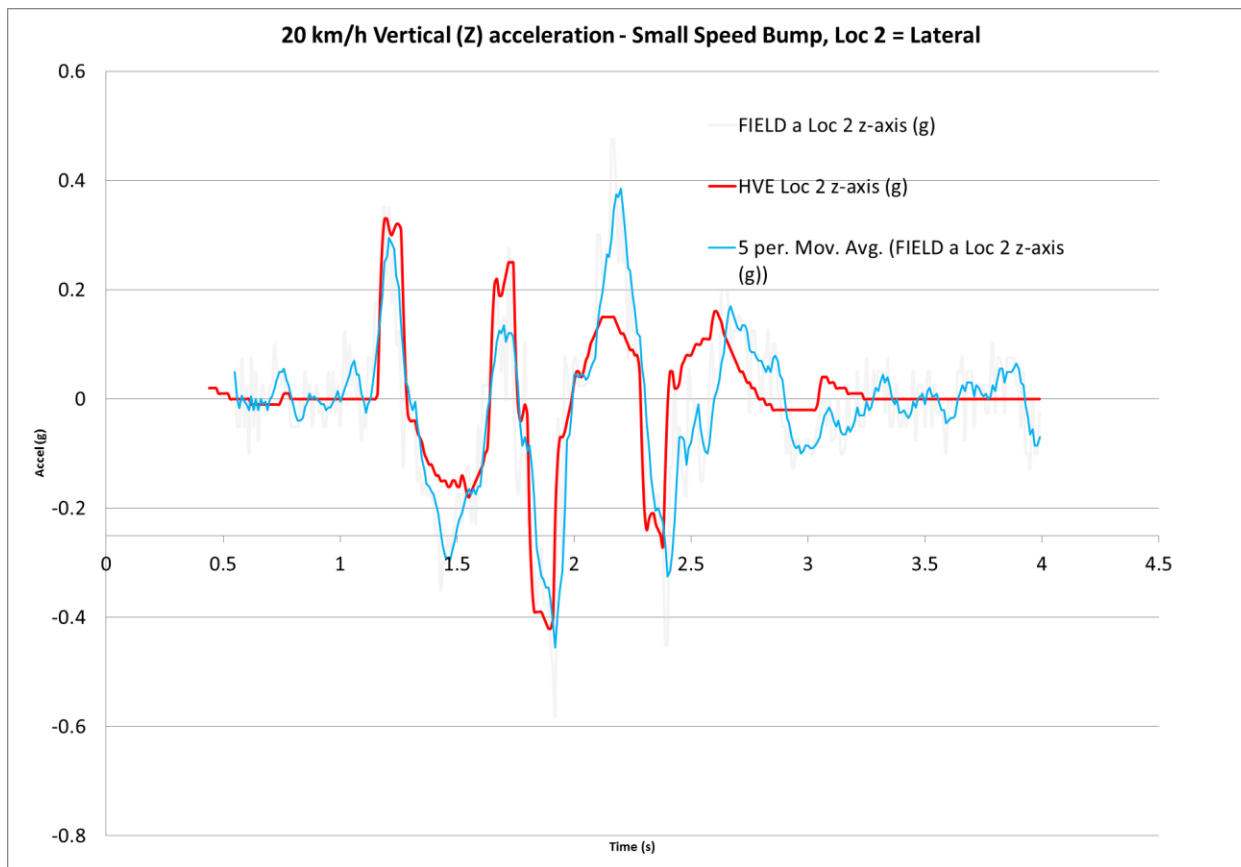


10 km/h Vertical (Z) acceleration - Large Speed Bump, Loc 3 = RRH



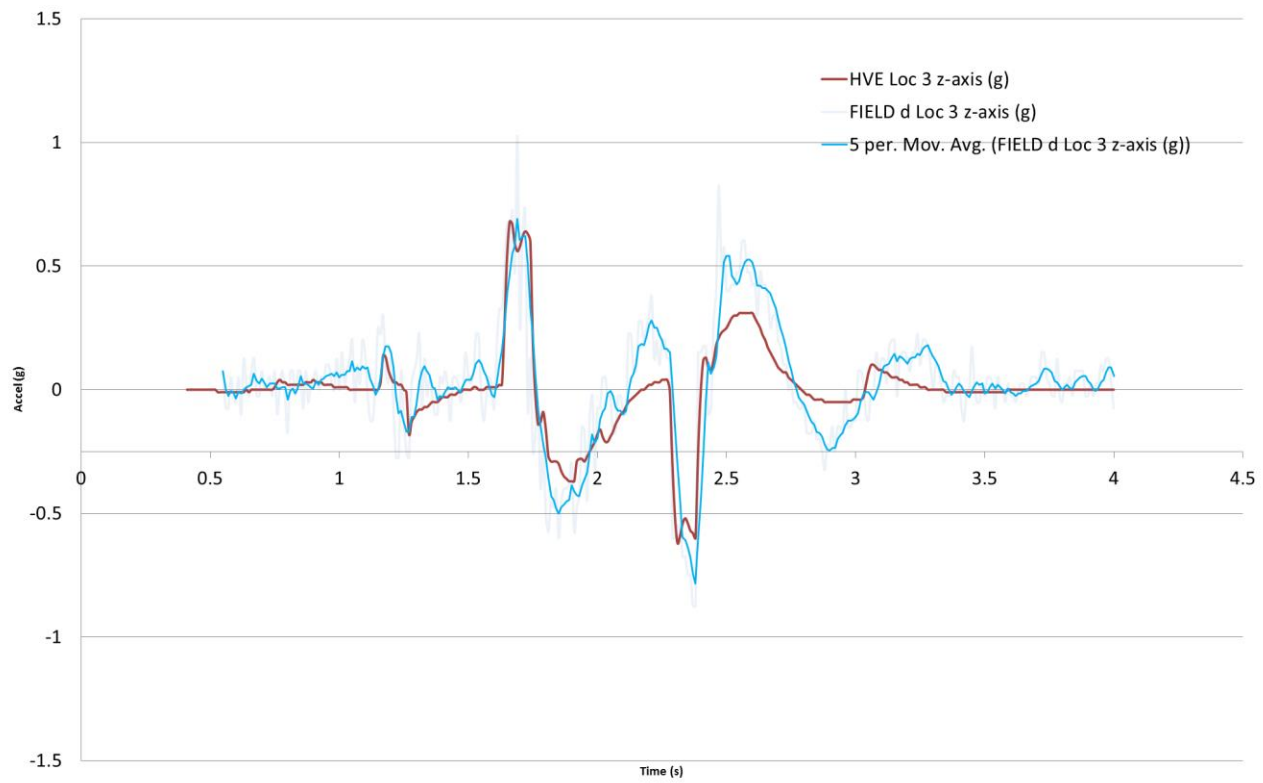




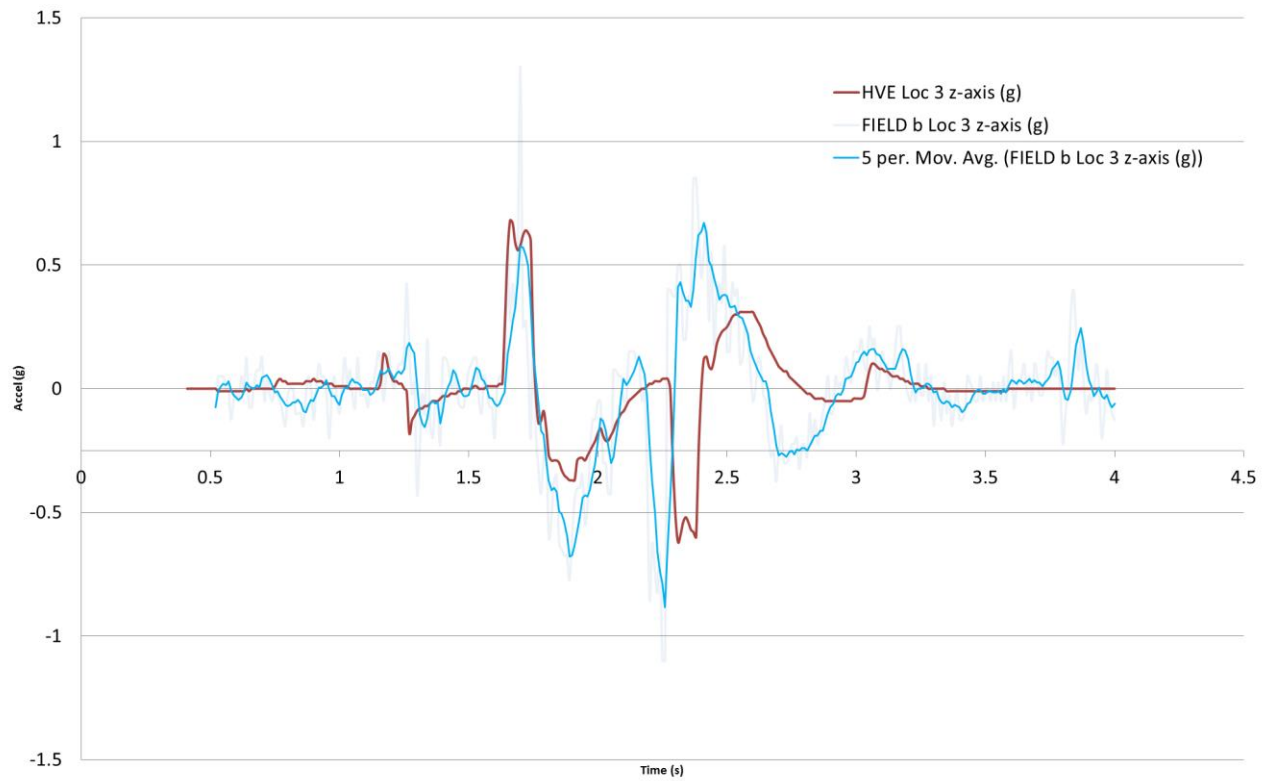


(Note: above is the only case for Location 2 on 20 km/h small bump z-axis. There is no best/worst case for this condition.)

20 km/h Vertical (Z) acceleration - Small Speed Bump, Loc 3 = RRH

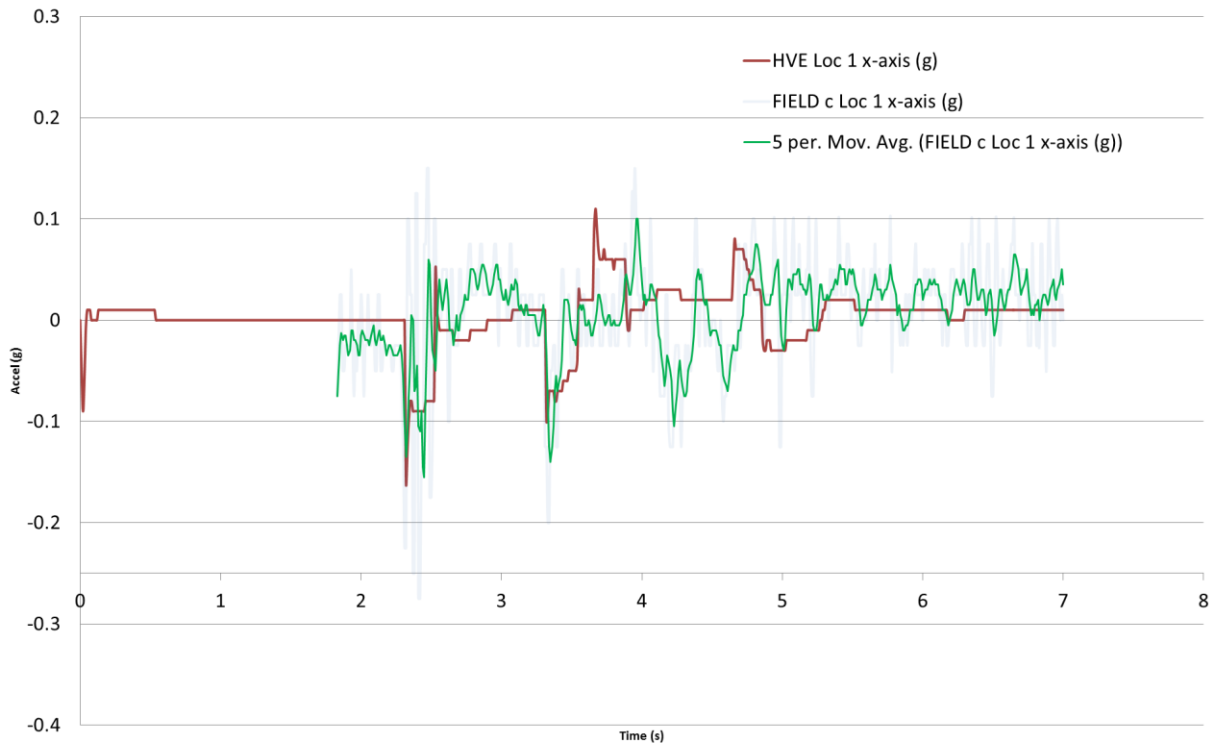


20 km/h Vertical (Z) acceleration - Small Speed Bump, Loc 3 = RRH



## **APPENDIX B – ACCELERATION COMPARISON PLOTS: X and Y Axes**

10 km/h Longitudinal (X) acceleration - Small Speed Bump, Loc 1 = near CM



10 km/h Lateral (Y) acceleration - Small Speed Bump, Loc 2 = Lateral

