HVE-WP-2023-01

# Building and Validation of a Battery Electric Vehicle (BEV) for HVE

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**2023 HVE Forum**
**Ft. Myers, FL**
**February 20 –24, 2023**

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## Abstract

HVE is a powerful tool for accurately reconstructing numerous types of vehicle-related accidents. One of the fundamental pillars for creating an accurate simulation is having the necessary data to build the proper vehicles. The Engineering Dynamics Company and Vehiclemetrics vehicle databases combined contain well over 500 vehicles. All of the vehicles currently within HVE or available for purchase separately are built around a conventional internal combustion engine drivetrain with either an automatic or manual transmission. However, with advances in vehicle powertrains, today's modern vehicles do not necessarily need to use a gasoline or diesel engine via transmission to propel the vehicle. Instead, electric motors placed at individual wheels drive the vehicle while using a battery pack for on-board energy storage. While on the surface a BEV's powertrain is significantly different from its engine/transmission counterpart, the fundamental parameters within HVE to build custom vehicles can be used to replicate a BEV drivetrain. For this study, a 2021 Ford Mustang Mach-E was tested dynamically to determine acceleration performance and measured statically to determine vehicle loading characteristics and suspension geometry and properties. Results from the testing and measurements were then used to build a custom vehicle within the HVE environment and validate the model.

## Introduction

The modern electric vehicle can trace its roots back to General Motor's EV1 which was produced in the late 1990s. Customer reaction was generally positive, even though the EV1 program was ultimately cancelled by General Motors after only a few years. Other mass-produced electric vehicles would follow, such as the Chevrolet Volt and Nissan Leaf, although neither were considered a commercial sales success. Lack of driving range, charging infrastructure, and higher sticker prices all contributed to customers' reluctance to switching from internal combustion engine vehicles to pure BEVs. However, BEVs finally began to find customer acceptance due to falling battery costs, more stringent emission regulations, and government BEV incentive purchase programs. Tesla alone sold over 900,000 BEVs in 2021 out of a total of 4.6 million BEVs according to LMC Automotive [1]. In its International Energy Outlook 2021 [2], the U.S. Energy Information Administration (EIA) estimated 1.31 billion vehicles comprised the global light-duty fleet in 2020, which it expects to grow to 2.21 billion by 2050. EIA also expects electric vehicles to grow from 0.7% of the global light-duty fleet in 2020 to 31% in 2050, reaching a total of 672 million vehicles.

With the potential substantial growth in BEVs as part of the global fleet, the reconstructionist is likely to increasingly encounter BEVs as part of their casework. As such, the reconstructionist must be able to model this nontraditional drivetrain correctly to accurately predict its dynamic response. Building a custom vehicle in HVE has been previously documented. The authors chose to follow a similar procedure as outlined in the HVE White Papers authored by Garvey [3] and Jadischke et al. [4] which included the data gathering procedures, measurement process, default data for certain non-measured mechanical parameters, and vehicle geometry creation.

## General Vehicle Information

A 2021 Ford Mustang Mach-E (Figure 1) was chosen by the authors for modeling of a BEV within HVE. The Mach-E is built on the Global Electrified 1 platform, which is a modified version of the Ford C2 platform that is used on both the fourth generation Ford Focus and fourth generation Ford Escape. Thus, as a starting point for creating the Mustang Mach-E in HVE, the Vehiclemetrics 2020-2021 Ford Escape was used as a building block and subsequently modified to fit the Mustang Mach-E's specifications.

***Figure 1.*** *2021 Ford Mustang Mach-E.*

The following general vehicle information was collected via visible inspection of the vehicle and by decoding the vehicle's Vehicle Identification Number and entered into the Vehicle Information dialog in the vehicle editor.

- Vehicle Name: Ford Mustang Mach-E
- Vehicle Type: Sport-Utility
- Make: Ford
- Model: Mustang Mach-E
- Year: 2021
- Body Style: Premium
- Number of Axles: Two
- Driver Location: Left
- Engine Location: Front
- Drive Axle(s): Axle Nos. 1 and 2

**Dimensional and Mass Data**

The Mustang Mach-E was three-dimensionally scanned with a FARO Focus$^{S}$ 70 laser scanner. Multiple scans were taken of both the exterior and interior of the vehicle to capture its geometry. Figure 2 shows a five-view image of the three-dimensional scan data of the Mustang Mach-E. The total mass of the vehicle and longitudinal and lateral center of gravity (CG) locations were determined using four wireless scales at each wheel location and using the equations presented in Jadischke et al. [4]. Expert Autostats was used to obtain the vertical CG location. Vehicle dimension and mass properties are shown in Table 1.


***Figure 2.*** *Five-view image of the scan data of the Mustang Mach-E with calculated CGx, CGy, and Expert Autostats CGz location (yellow sphere).*

***Table 1.*** *Dimensional data.*

| Parameter | Value | Units |
|---|---|---|
| CG to front | 99.1 | in |
| CG to rear | 86.5 | in |
| CG to right side | 35.1 | in |
| CG to left side | 38.9 | in |
| CG to roof | 38.9 | in |
| CG to undercarriage | 19.3 | in |
| Wheelbase | 117.5 | in |
| Front track width | 63.5 | in |
| Rear track width | 63.4 | in |

The left front wheel was removed and the weight was recorded (see Table 2). For a vehicle equipped with independent suspension, it is assumed the unsprung mass at each wheel is equal to the mass of the tire plus the mass of the rim. This weight was entered in the tire physical property menu within HVE's vehicle editor.

**Stiffness Coefficients**

No crash tests were available for the Mustang Mach-E for either the front, rear, or side through publicly available sources. Class category front, rear, and side A, B, and Kv stiffness coefficients were assigned according to Siddall and Day [5] for a Multi-Purpose Class 1 vehicle. Roof and undercarriage stiffnesses were set as EDC defaults.

## Inertial Properties

HVE provides the option to auto update the inertial properties of a vehicle based on the user-entered vehicle weight. The inertias for light-duty vehicles are calculated using this weight and are based on best fit curves from work initially performed by NHSTA and subsequently updated by others [6]. The authors used the same method employed by EDC. Values entered into HVE's Inertial Data dialog in the Inertias menu are shown in Table 2.

***Table 2.*** *Mass and inertia data.*

| Parameter | Value | Units |
|---|---|---|
| Total vehicle weight | 4563 | lb |
| Roll inertia | 7269.31 | lb-sec-in$^2$ |
| Pitch inertia | 34946.08 | lb-sec-in$^2$ |
| Yaw inertia | 35671.03 | lb-sec-in$^2$ |
| Wheel weight | 56 | lb |

## Suspension Properties

The wheel rate, which can be defined as the vertical force per unit of vertical displacement of the wheel relative to the vehicle, was measured. This was obtained by placing the vehicle on four wireless scales. A cloth tape measure was dropped from the left front wheel arch to the center of the left front wheel (Figure 3). The vehicle was raised with a floor jack and the weight and corresponding displacement was recorded incrementally until the scale read zero weight. The process was repeated as the vehicle was lowered back down onto the scale. The data for the up and down directions were plotted and the slope of the linear regression is equal to the wheel rate. The average of the up and down slopes were taken to get the wheel rate for each side of the suspension. The process was then repeated for the left rear wheel. The authors assumed the right front wheel rate and the right rear wheel rate were equal to the rates obtained from the left side of the vehicle. Figure 4 and Figure 5 show the front and rear wheel rates, respectively.

The damping at each wheel was approximated from the wheel rate using the equations found in Garvey [3], specifically:

$$Damprate = \sqrt{\frac{K}{M}} \qquad (1)$$

where:

$K$ = wheel rate
$M$ = mass of the suspension at that tire

$$M = \frac{x}{Wb} \times CW \times 0.5/386.4 \qquad (2)$$

where:

$x$ = distance from the CG to the axle (in)
$Wb$ = wheelbase (in)
$CW$ = curb weight (lb)

To determine auxiliary roll stiffness, measurements were taken of the upper control arm from the bolt to outer tire, ball joint to outer tire, and bolt to bolt according to Figure 6. The sway bar's diameter was also measured.

Using Figure 6, the installation ratio, $I_r$, can be defined as:

$$Ir = \frac{r_2}{r_1} = \frac{r_1 - r_4}{r_1} = 1 - \frac{r_4}{r_1} \qquad (3)$$

***Figure 3.*** *Wheel rate measuring process.*

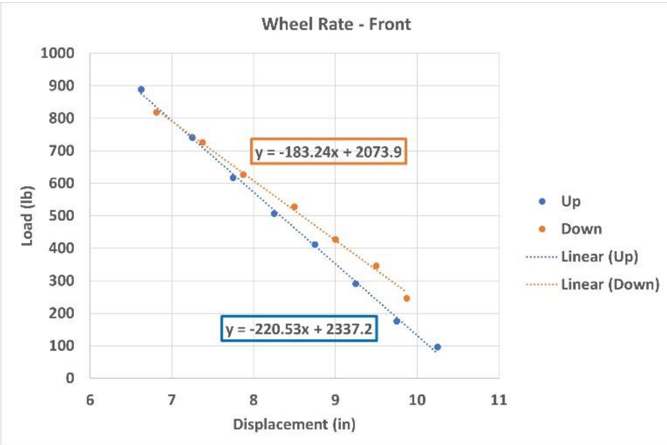


***Figure 4.*** *Front wheel rate.*

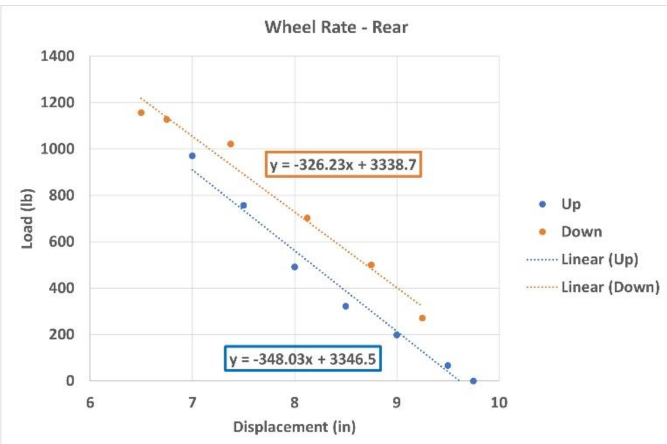


***Figure 5.*** *Rear wheel rate.*

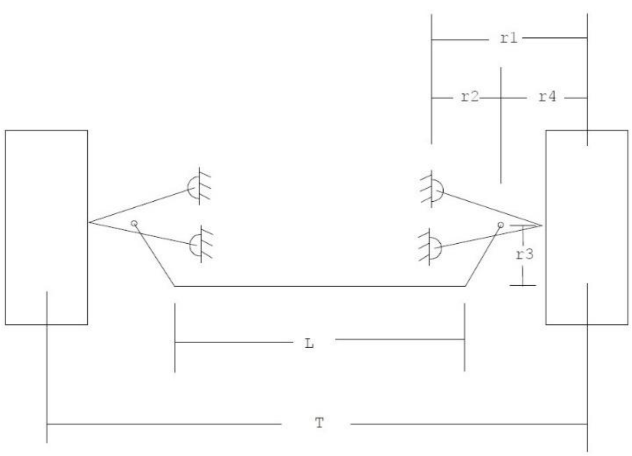


***Figure 6.*** *Front suspension measurements, top view.*

and the anti-roll bar torsional stiffness, $K_B$, can be defined as:

$$K_B = \frac{\pi}{32}\frac{D^4 G}{L} \qquad (4)$$

where:

$D$ = diameter of anti-roll bar (in)
$G$ = torsional elasticity (psi)
$L$ = length of anti-roll bar (in)

and the auxiliary roll stiffness, $K\varphi_b$, can be defined as:

$$K\varphi_b = \frac{K_B \, I_r^2 T^2}{r_3^2} \qquad (5)$$

where:

$K_B$ = anti-roll bar torsional stiffness (in-lb)/rad
$Ir$ = installation ratio
$T$ = front track width (in)
$r_3$ = distance from ball joint to outer tire (in)

Table 3 shows the values used for the Mustang Mach-E's front and rear wheel rates and auxiliary roll stiffnesses.

***Table 3.*** *Suspension data.*

| Parameter | Value | Units |
|---|---|---|
| Front wheel rate | 201.89 | lb/in |
| Rear wheel rate | 337.13 | lb/in |
| Damping at front wheel | 7.873 | (lb-sec)/in |
| Damping at rear wheel | 11.339 | (lb-sec)/in |
| Front aux. roll stiffness | 12485.36 | (in-lb)/° |
| Rear aux. roll stiffness | 0 | (in-lb)/° |

The remainder of data needed to enter into the Suspension dialog includes the following:

- Lateral load transfer coefficient
- Coulomb friction
- Friction null band
- Maximum deflection to jounce/rebound stop
- Linear deflection rate of stop
- Cubic deflection ratio of stop
- Energy ratio of stop

The above parameters were left as the default values for the Vehiclemetrics 2020-2021 Ford Escape platform for which the Mustang Mach-E is being built. Additionally, alignment data versus jounce and rebound were also left as default values for the Ford Escape.

**Steering Properties**

The number of steering wheel rotations to full left lock and full right lock were recorded. The tire angle for both the left and right tires when at full left and right lock were calculated by extending a chalk line from the outside of the tire towards the front of the vehicle in both the locked and straight positions (Figure 7). The Ackermann angle was also calculated.

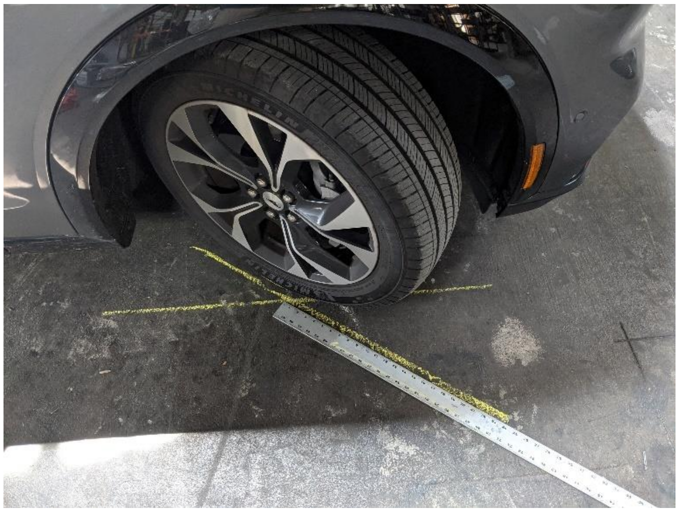

***Figure 7.*** *Tire angle measurements.*

***Table 4.*** *Steering data.*

| Parameter | Value | Units |
|---|---|---|
| Steering gear ratio | 14.2 | deg/deg |

The remainder of data needed to enter into the Steering System dialog includes the following:

- Steering coulomb friction
- Steering column inertia
- Steering column stiffness
- Steering linkage mass
- Steering linkage stiffness
- Steering linkage damping
- Steering friction lag

The above parameters were left as the default values for the Vehiclemetrics 2020-2021 Ford Escape platform for which the Mustang Mach-E is being built.

**Brake Properties**

A generic brake pedal ratio for a Multi-Purpose Class 1 vehicle was used form Sidall and Day [5]. Torque ratio was calculated using HVE's Brake Designer for disc brakes. The following data was collected from a subscription-based online vehicle repair guide:

***Table 5.*** *Brake data.*

| Parameter | Value | Units |
|---|---|---|
| Outer diameter, front | 14.25 | in |
| Outer diameter, rear | 12.19 | in |
| Inside diameter, front | 10.00 | in |
| Inside diameter, rear | 7.94 | in |
| Rotor thickness, front | 1.25 | in |
| Rotor thickness, rear | 0.81 | in |
| Lining thickness | 0.40 | in |
| Number of pistons, front | 4 | |
| Number of pistons, rear | 1 | |
| Pistion diameter, front | 1.75 | in |
| Piston diameter, rear | 1.62 | in |

Currently, the Brake Designer does not allow for more than three pistons. As such, an equivalent piston diameter was calculated for the front four pistons and converted to a two-piston system. The remainder of data needed to enter into the Brake Designer dialog includes the following:

- Included angle
- Mechanical efficiency

The above parameters were left as the default values for the Vehiclemetrics 2020-2021 Ford Escape platform for which the Mustang Mach-E is being built.

**Tire Properties**

The Mustang Mach-E was equipped with Michelin Primacy A/S 225/55R19 tires. Tire pressures were at manufacturer's recommended settings. A 225/55R19 tire was available in the Generic tire database. No changes were made to the default values in the physical data, frictional data, corning stiffness data, camber stiffness data, and slip vs. roll-off data other than adjusting the tire/wheel weight to the proper value for the Mustang Mach-E (see Table 2).

**Powertrain Properties**

The motor used in a BEV uses current which flows through a magnetic field creating an electromotive force (EMF) necessary to rotate the armature to get the vehicle moving. This process also creates "back EMF" which is proportional to the motor speed, thereby decreasing torque output with increasing motor speed. Thus, for a motor speed of near 0 rpm, there is little to no back EMF and the maximum torque the motor can produce is available to the driver. Back EMF is also the reason why the torque curve begins to drop off as the electric motor speed increases. For the wide-open throttle curve, the Mustang Mach-E's estimated horsepower vs. motor speed is shown in Figure 8 with a maximum rated horsepower of 346 hp and 428 lb-ft of torque.

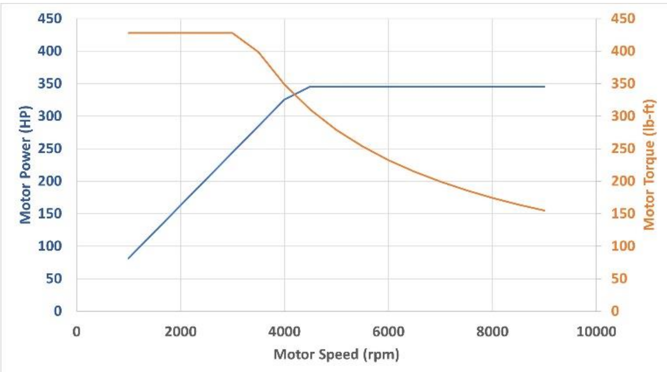


***Figure 8.*** *Estimated torque/horsepower curve [7].*

Closed throttle curve calculations for friction horsepower for an internal combustion engine is modeled by the equation found in Garvey [3]. The equation relies on knowing values for compression ratio, stroke, engine displacement, and engine speed, all parameters related specifically to an internal combustion engine. As such a closed throttle curve was empirically derived from vehicle testing (see HVE Validation section) for the Mustang Mach-E's electric motor.

The additional data required for the Drivetrain dialog are:

- Engine idle speed
- Drivetrain inertia

As neither of these parameters directly relate to a BEV's powertrain, these two parameters will be investigated further in the HVE Validation portion of this study.

The Mustang Mach-E is not equipped with a transmission and was therefore modeled as a 2-speed (the minimum number of required gears in HVE) manual transmission. Differential ratio was obtained through manufacturer specifications. Table 6 shows the transmission and differential data.

***Table 6.*** *Transmission and differential data.*

| Parameter | Value | Units |
|---|---|---|
| Number of gears | 1 | |
| 1st gear ratio | 1.00 | |
| Final drive ratio | 9.05 | |

**Aerodynamic Drag Properties**

The drag coefficient for the front of the Mustang Mach-E was obtained through manufacturer's specifications. The center of pressure in the X-direction was set to the distance from the CG to the front of the vehicle. Projected surface area was calculated from the scan data (Figure 9). Table 7 shows the aerodynamic drag data.


***Figure 9.*** *Projected front surface area.*

***Table 7.*** *Aerodynamic drag data.*

| Parameter | Value | Units |
|---|---|---|
| Drag coefficient | 0.285 | |
| Projected surface area | 3610.08 | $in^2$ |
| CG to front | 99.1 | in |

**Vehicle Geometry**

Commercially available modeling software was used to generate vehicle geometry compatible with HVE. To create the geometry, the three-dimensional laser scan data (Figure 10) provided millimeter accurate reference in three-dimensional space allowing for modeling the exterior of the vehicle (Figure 11) using a semi-uniform grid spacing of the four-sided polygon modeling method outlined in Jadischke et al. [4].

***Figure 10.*** *Ford Mustang Mach-E scan data.*

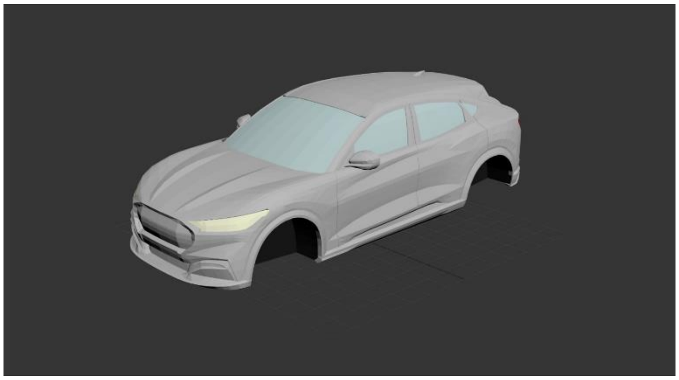

***Figure 11.*** *Ford Mustang Mach-E three-dimensional model.*

To function within HVE as a crushable vehicle model, the vehicle geometry must be one, water-tight object with no holes or boundaries. HVE generates wheels for simulation, so while their position relative to the geometry was noted, the wheels themselves were omitted from the three-dimensional model. Multiple materials were applied to the mesh so windows, headlights, taillights, and body can be distinguished.

The vehicle geometry was then exported for use in HVE. Before exporting, the model must be positioned and oriented in three-dimensional space relative to HVE's coordinate system. The identified CG of the vehicle was placed at the origin of the three-dimensional environment [0,0,0], and the model rotated relative to the X-, Y-, and Z-axes such that the resulting model would import in the correct orientation, positive X – forward, positive Y – to the right, and positive Z – down.

## HVE Validation

Vehicle testing was conducted in a limited access business park on an asphalt-paved, dry surface. An aerial of the location is shown in Figure 12. The area was also scanned with a FARO Focus$^S$ 350 3D laser scanner which was used to generate a point cloud of the road surface (Figure 13).

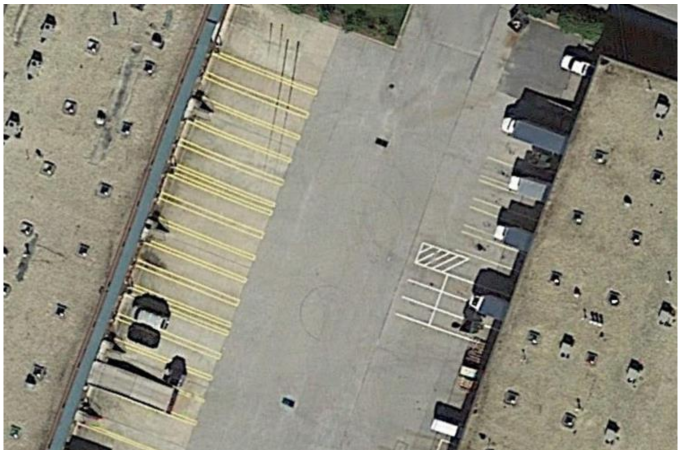

***Figure 12.*** *Aerial view of location of testing.*

***Figure 13.*** *Testing location 3D point cloud.*

The Mustang Mach-E was instrumented with several data logging sensors and devices, including a Racelogic Video VBOX Pro, capable of sampling at 20 Hz. Parameters of interest monitored continuously by the VBOX include position and speed, both via GPS, along with associated calculated parameters. Additionally, the VBOX utilized an Inertial Measurement Unit (IMU) RLVBIMU04, which continuously monitored longitudinal, lateral, and vertical accelerations. The IMU and VBOX were securely mounted prior to each test run. The video input of the VBOX used an internally-mounted camera to monitor vehicle accelerator and brake pedal application and an exterior camera mounted above the vehicle's front axle to confirm vehicle travel distance. A GoPro Hero 8 was also used to capture additional GPS and acceleration data, as well as to record the screen of an Innova 5410 scan tool, which is capable of live, real-time, data stream including throttle pedal position.

The Mustang Mach-E is equipped with three different driving modes: Unbridled, Engage, and Whisper. While throttle mapping is changed for each mode, the three drive modes offer maximum available horsepower, with the difference coming from how much throttle input the driver needs to access that horsepower. Besides changes in steering wheel stiffness, the main difference between the three models is the level of regenerative braking while coasting, with Unbridled, Engage, and Whisper being the most aggressive to least aggressive.

For each of the three drive modes, the authors performed 0-40 mph acceleration runs at 100% throttle application. The accelerator pedal was then released and the vehicle was allowed to coast. Maximum deceleration testing was also performed from 45 mph and 60 mph.

Acceleration

Testing confirmed that at 100% throttle input, drive mode had little-to-no effect on available acceleration levels. Table 8 shows the results of the acceleration testing. On average, 40 mph was reached at approximately 97.0 ft at an average acceleration of approximately 0.51 g for the three different drive modes.

***Table 8.*** *Acceleration testing results.*

| Drive Mode | Speed (mph) | Distance (ft) | Ave Accel (g) | Peak Accel (g) |
|---|---|---|---|---|
| Whisper | 40.0 | 96.1 | 0.52 | 0.62 |
| Engage | 40.3 | 97.1 | 0.51 | 0.61 |
| Unbridled | 40.3 | 97.7 | 0.50 | 0.63 |

With the assumed horsepower/torque curve shown in Figure 8, drivetrain inertia and engine idle speed were independently varied to get the best match to the VBOX data. An idle speed of 850 rpm and drivetrain inertia of 0 lb-sec$^2$-in produced the best the results. Setting the drivetrain inertia to 0 lb-sec$^2$-in makes sense in regards to a BEV drivetrain due to these types of vehicles lacking a transmission, clutch/torque converter, and driveshaft equating to less rotating mass. The comparison between the VBOX data and HVE simulations for Engage drive mode are shown in Figure 14 and Figure 15 for speed vs. distance and acceleration vs. distance, respectively. Results for Unbridled and Whisper drive modes can be found in Appendix A.

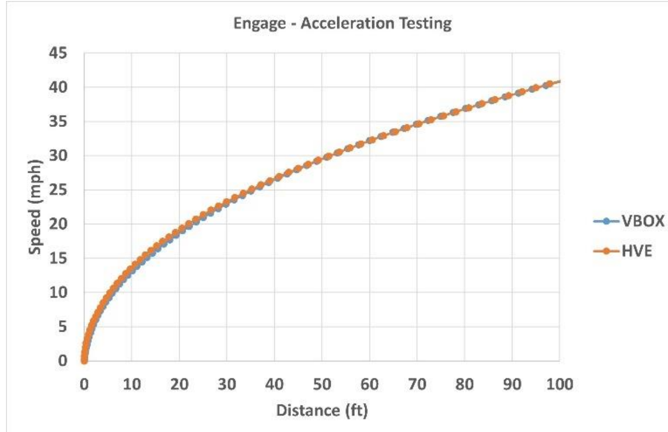


***Figure 14.*** *Speed vs. distance testing results; drive mode Engage.*

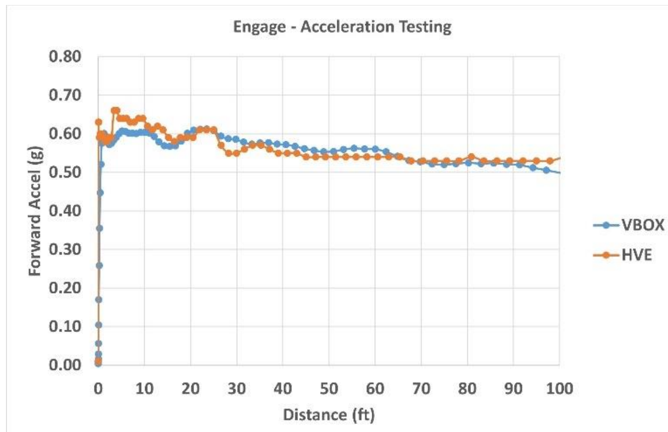


***Figure 15.*** *Acceleration vs. distance testing results; drive mode Engage.*

Figure 14 and Figure 15 show good agreement between the VBOX data and the HVE simulations.

Coasting/Regenerative Braking

The effect of the three different drive modes was apparent in the coasting/regenerative brake testing. Results are shown in Table 9.

***Table 9.*** *Coast/regenerative braking testing results.*

| Drive Mode | Ave Accel (g) | Peak Accel (g) |
|---|---|---|
| Whisper | -0.02 | -0.06 |
| Engage | -0.06 | -0.08 |
| Unbridled | -0.12 | -0.14 |

Results indicate the average deceleration level approximately doubles each time when going from the least to most aggressive regenerative braking strategy.

Friction braking for an internal combustion engine-equipped vehicle is handled by the closed throttle curve in HVE. This curve is estimated using the equation from Garvey [3]. However, the parameters used in this equation are unique to internal combustion engines. As such, coast down testing was performed so that a closed throttle curve could be derived for each of the Mustang Mach-E's drive modes. The method outlined in Timbario et al. [8] for engine torque calculation was used to generate a horsepower vs. rpm closed throttle curve; a torque multiplier was not needed. However, the testing location only provided approximately 200 ft to coast and activate regenerative braking, which was not adequate to reach a speed of 0 mph. As such, the closed throttle torque calculations could only be made for motor speeds in the 4,000-5,000 rpm range using the VBOX data. Therefore, motor speed vs. motor torque data for regenerative braking for motor speeds less than 4,000 rpm had to be obtained and used as surrogates [9]. Figure 16, Figure 17, and Figure 18 show the closed throttle curves for Whisper, Engage, and Unbridled. From Figure 16, Figure 17, and Figure 18, horsepower vs. rpm tables were generated (Table 10).

The comparison between the VBOX data and HVE simulations for Engage drive mode are shown in Figure 19 and Figure 20 for speed vs. distance and acceleration vs. distance, respectively. Results for Unbridled and Whisper drive modes can be found in Appendix B.

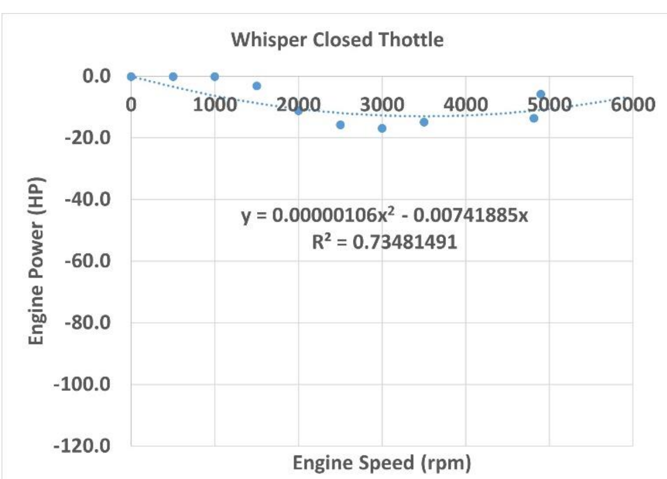


***Figure 16.*** *Closed throttle curve, Whisper drive mode.*

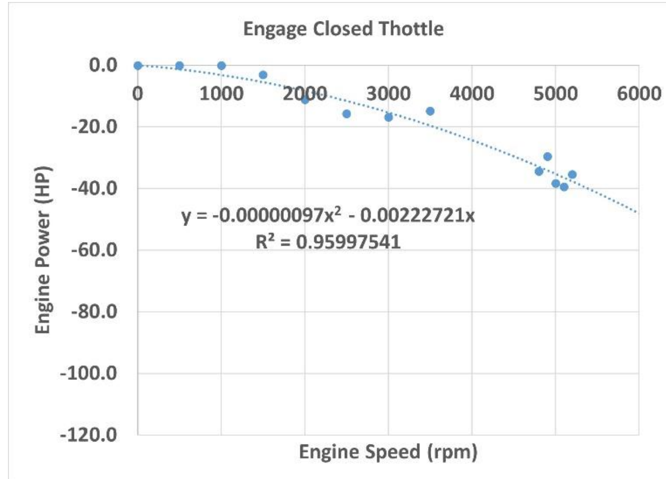


***Figure 17.*** *Closed throttle curve, Engage drive mode.*

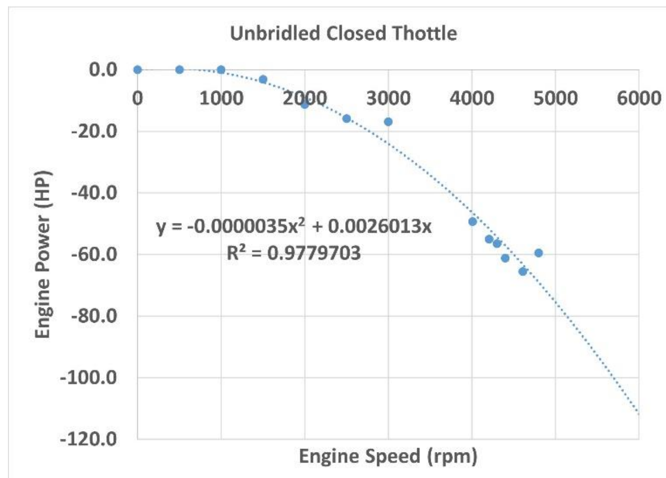


***Figure 18.*** *Closed throttle curve, Unbridled drive mode.*

***Table 10.*** *Horsepower vs. rpm table for the Whisper, Engage, and Unbridled drive modes.*

| | Whisper | Engage | Unbridled |
|---|---|---|---|
| RPM | HP | HP | HP |
| 1000 | -6.4 | -3.2 | -0.9 |
| 2000 | -10.6 | -8.3 | -8.7 |
| 3000 | -12.7 | -15.4 | -23.6 |
| 4000 | -12.7 | -24.4 | -45.5 |
| 5000 | -10.6 | -35.4 | -74.3 |
| 6000 | -6.4 | -48.3 | -110.2 |

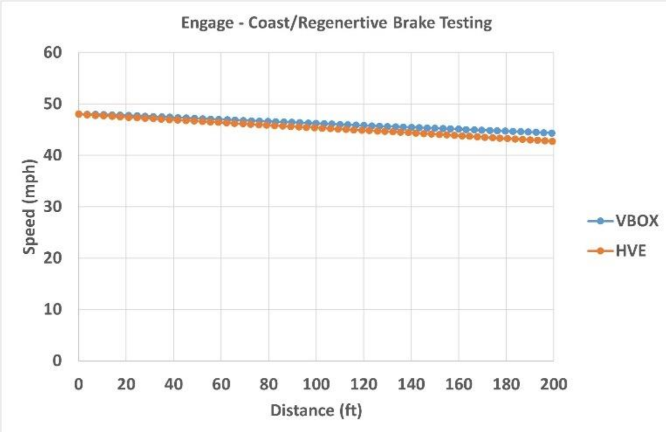


***Figure 19.*** *Speed vs. distance testing results; drive mode Engage.*

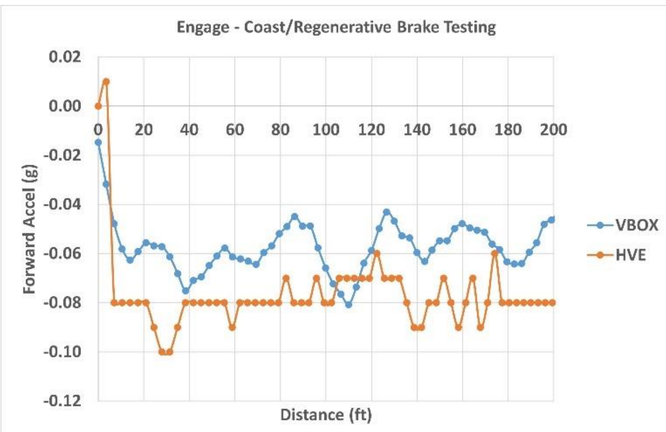


***Figure 20.*** *Acceleration vs. distance testing results; drive mode Engage.*

The HVE simulations are in general agreement with the VBOX testing but overpredicts the closed throttle deceleration levels in all three drive modes. This could be due to the use of surrogate motor torque data to fill in the lower motor speed horsepower values, which may not be representative of the Mustang Mach-E's motor.

<u>Braking</u>

Maximum braking tests were performed at 45 mph and 60 mph. Since maximum braking efficiency is available across all drive modes, brake testing was only performed in the default Engage drive model. Table 11 shows the brake testing results. On average, an average acceleration of approximately -0.83 g and a peak acceleration of -0.99g was achieved.

***Table 11.*** *Brake testing results.*

| Drive Mode | Speed (mph) | Distance (ft) | Ave Accel (g) | Peak Accel (g) |
|---|---|---|---|---|
| Engage | 45.4 | 80.7 | -0.82 | -1.00 |
| Engage | 59.6 | 140.2 | -0.83 | -0.99 |

Figure 21 and Figure 22 show the comparison to the HVE simulations for the 45-mph run for speed vs distance and acceleration vs. distance, respectively.

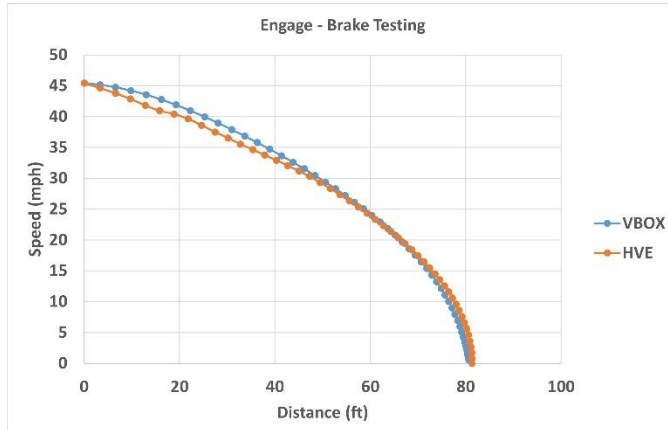


***Figure 21.*** *Speed vs. distance testing results; drive mode Engage.*

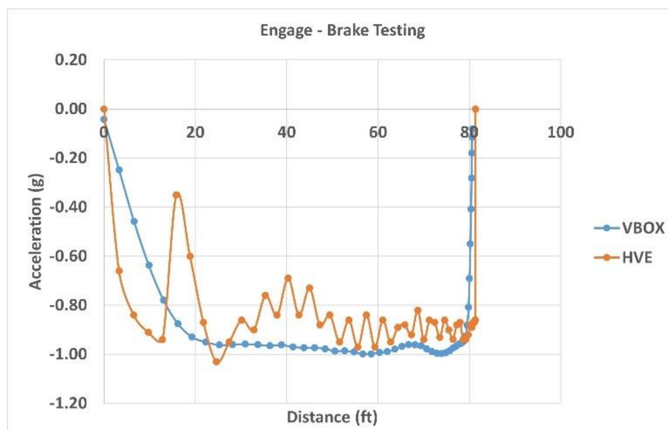


***Figure 22.*** *Acceleration vs. distance testing results; drive mode Engage.*

Figure 23 and Figure 24 show the comparison to the HVE simulations for the 60-mph run for speed vs distance and acceleration vs. distance, respectively.

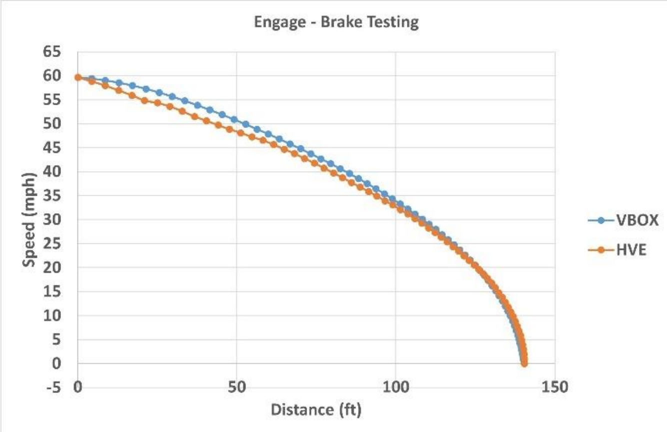


***Figure 23.*** *Speed vs. distance testing results; drive mode Engage.*

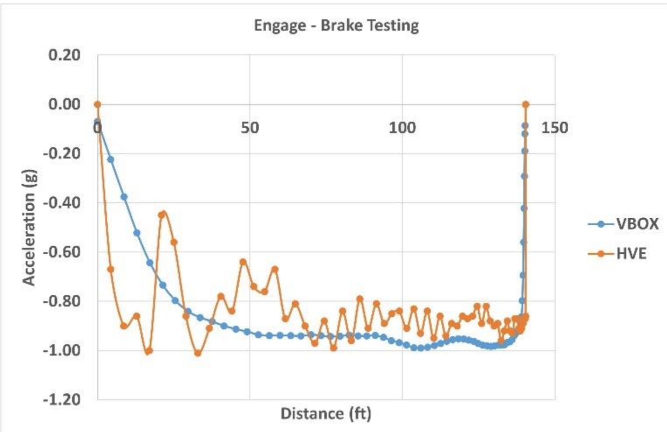


***Figure 24.*** *Acceleration vs. distance testing results; drive mode Engage.*

Figure 21, Figure 22, Figure 23, and Figure 24 show good agreement between the VBOX data and the HVE simulations. The variation in HVE's deceleration levels as compared to the VBOX data was found to be a related to both ABS parameters (ABS System Data) and applied pedal force (Driver Controls). Delay Method was set to Vehicle-Based and apply and release times were lowed from 0.05 sec to 0.02 sec. This, in combination with a pedal force of 90 lb produced the best results.

**Summary**

The study presents a methodology for building and editing the necessary HVE drivetrain inputs for a BEV. The process for building the vehicle follows closely the steps previously outlined in both Garvey [3] and Jadischke et al. [4]. Results from acceleration, coast-down, and brake testing show that minimal changes are required to properly model a BEV within the HVE environment. As expected, the most significant change is setting the drivetrain inertia to 0 lb-sec$^2$-in to compensate for the lack of rotating drivetrain components in a BEV.

This study also validates the methodology presented in Timbario et al. [8] used to calculate the closed throttle torque/horsepower curve in HVE.

**References**


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2. U.S. Energy Information Administration, *International Energy Outlook 2021 with Projections to 2050*, U.S. Department of Energy, Washington, D.C., 2021.
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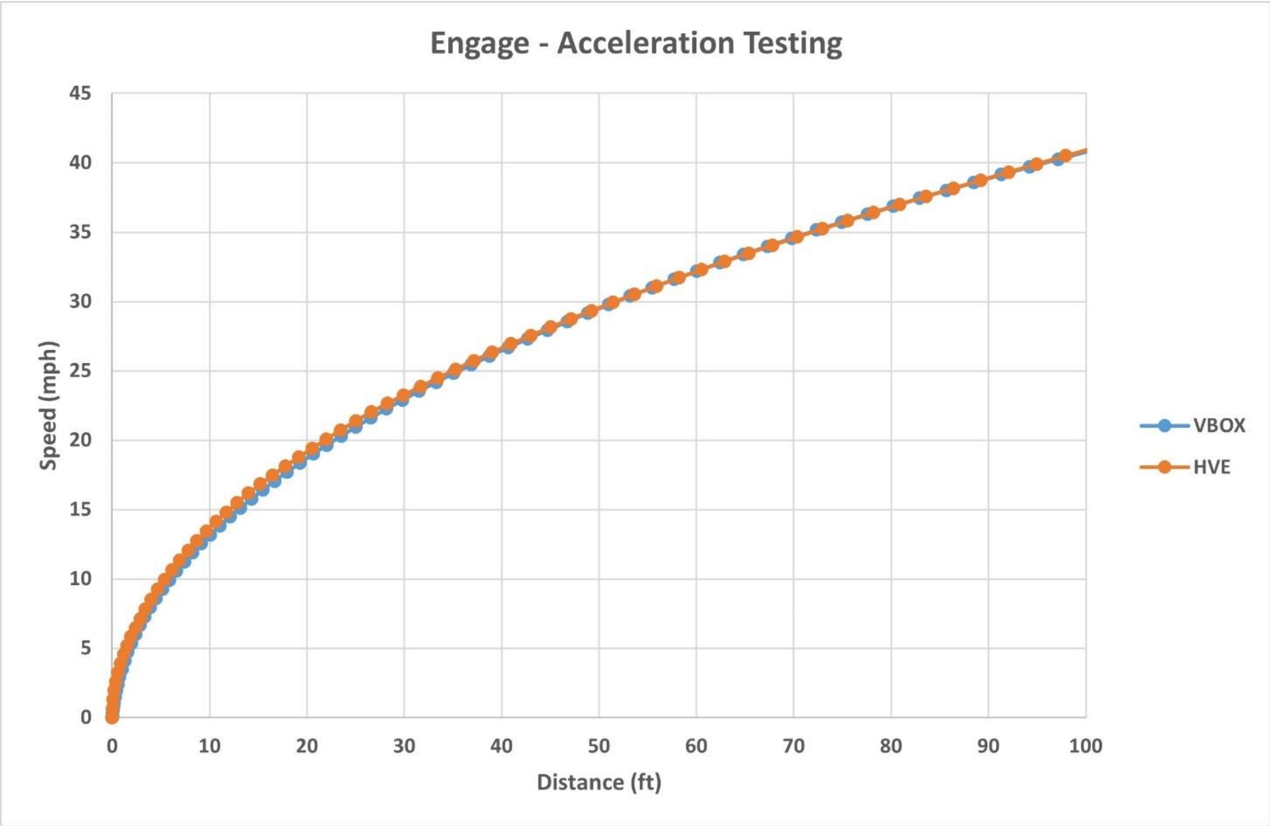
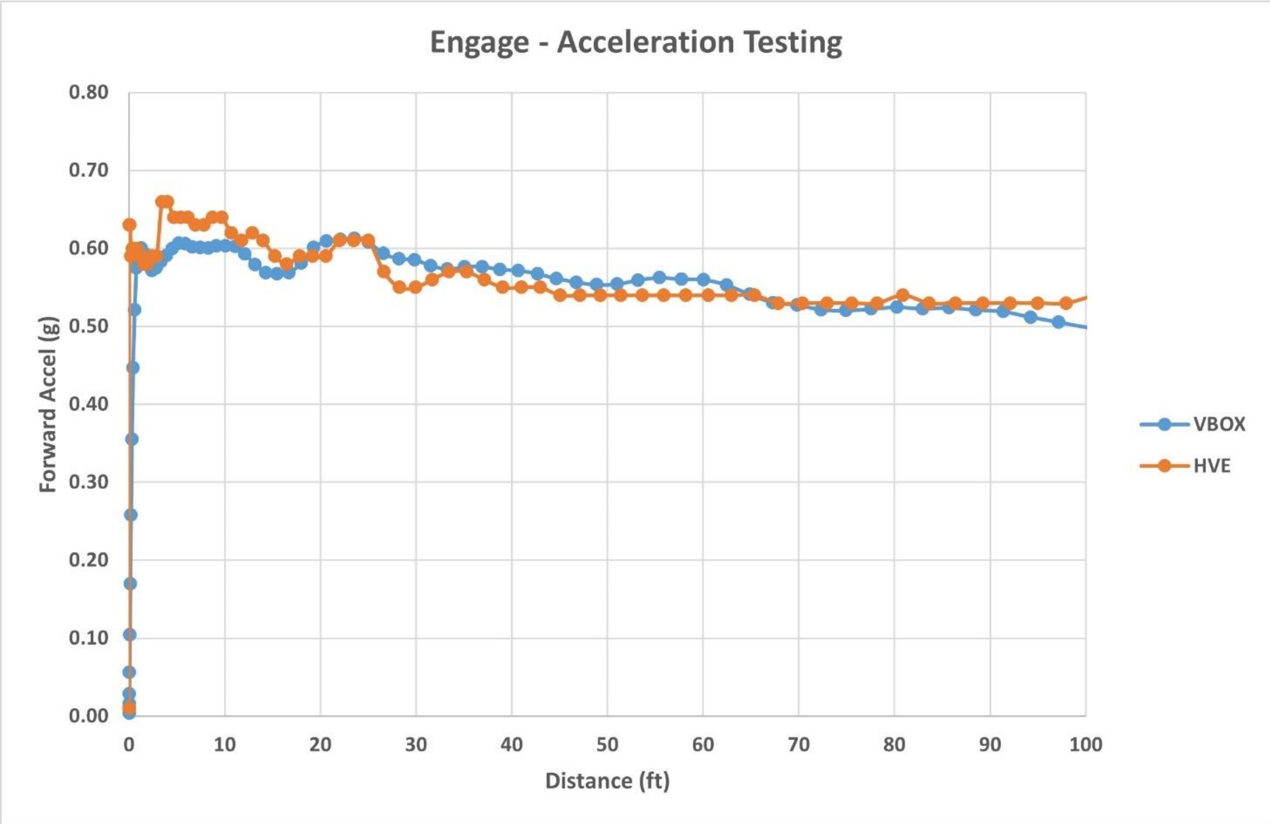
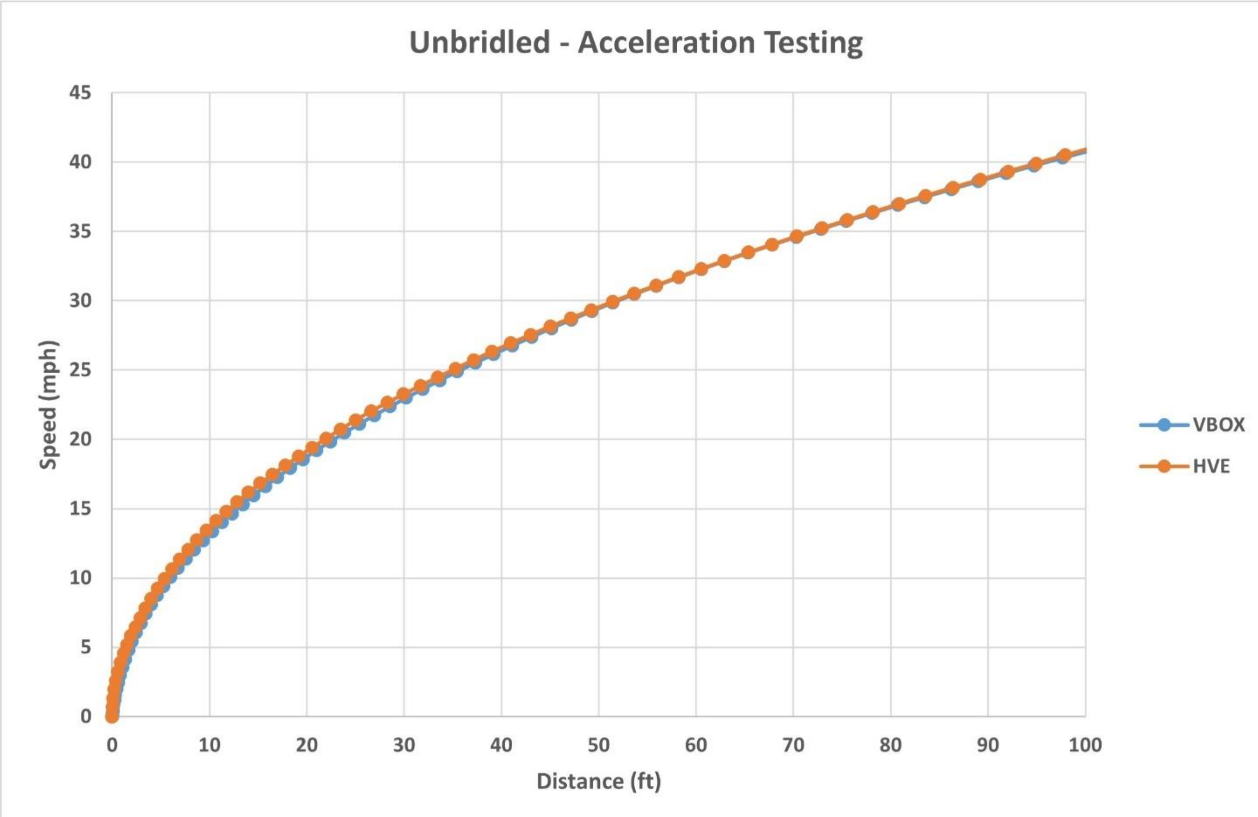
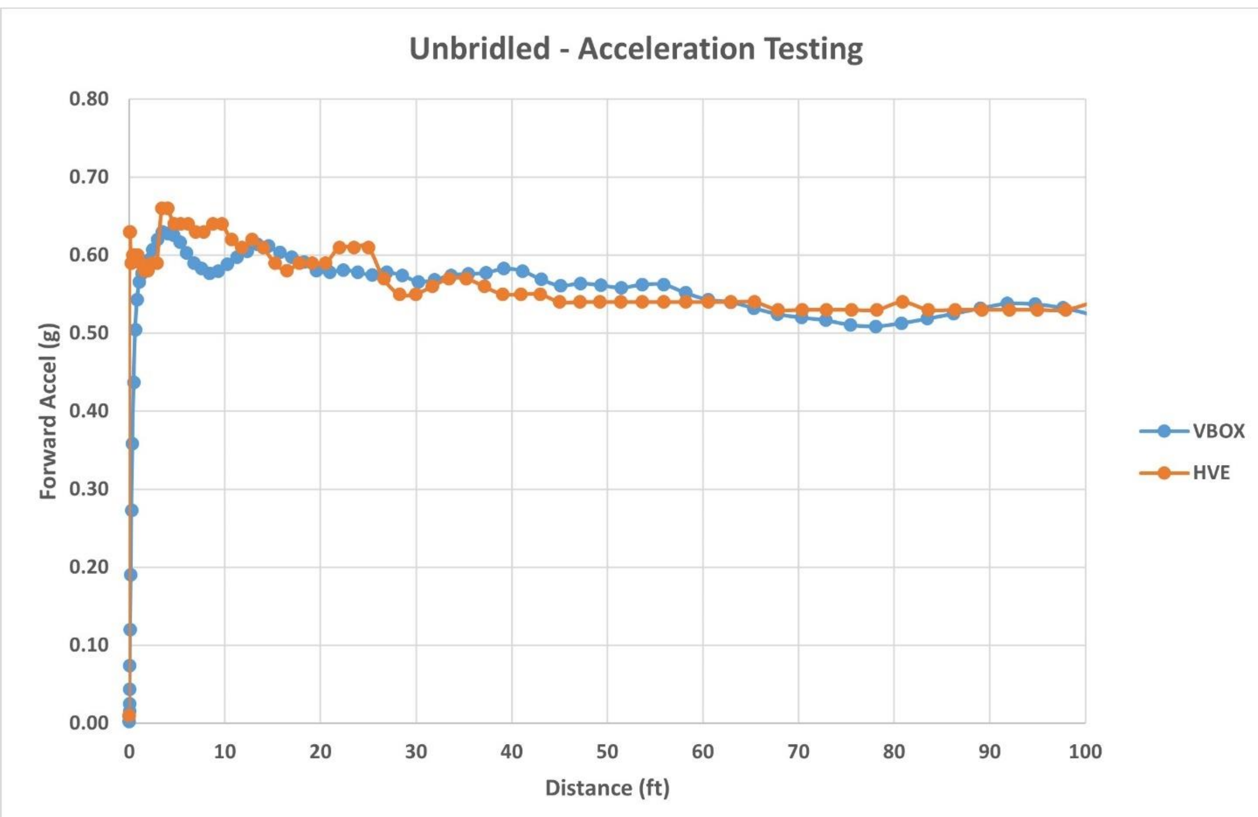
8. Timbario, T.A, Sheldon II, S., Stoner, J., and Nelson, J.D., *Testing and Modeling of Engine Idle Creep in Conventional Automatic-Equipped Vehicles*, WP-2022-1, Engineering Dynamics Company, Severna Park, MD, 2022.
9. Yeo, H. et al., *Regenerative Braking Algorithm For a HEV with CVT Ratio Control During Deceleration*, SAE International, Warrendale, PA, 2004.

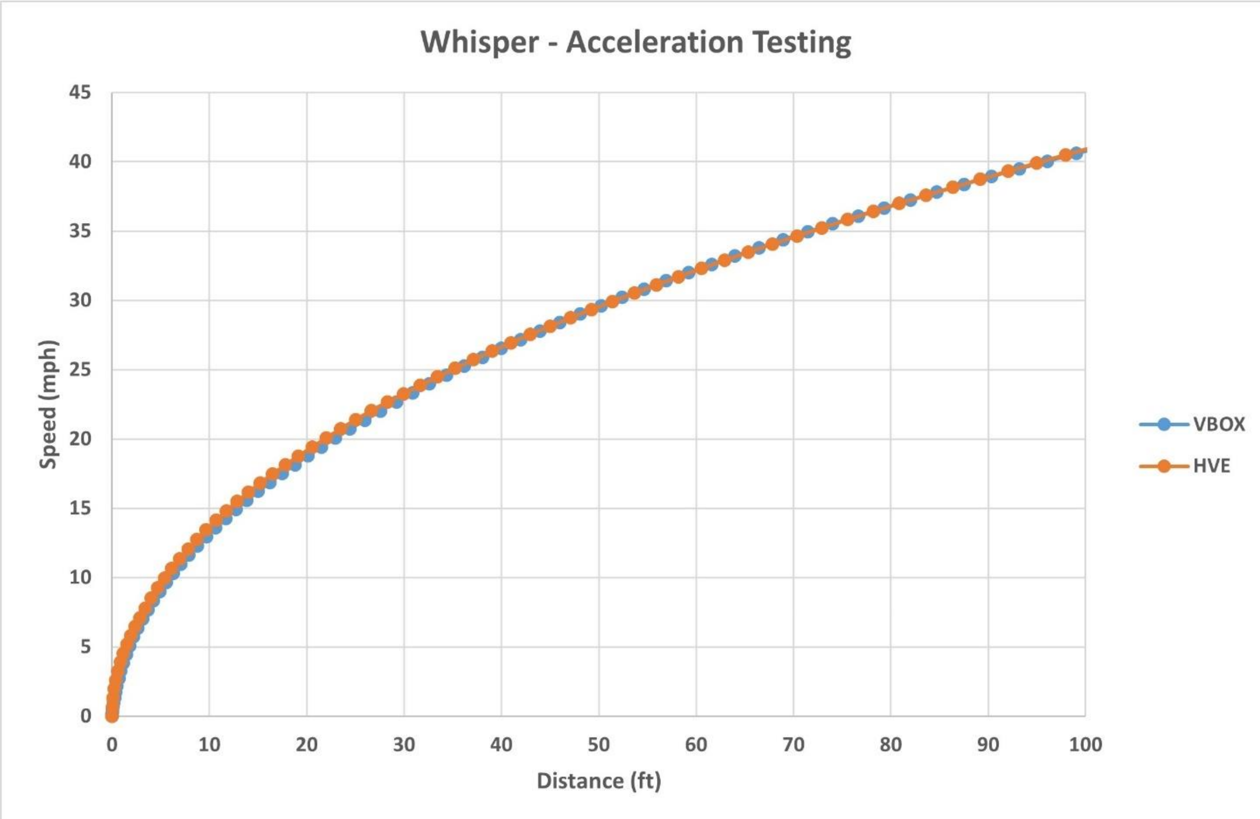
# APPENDIX A

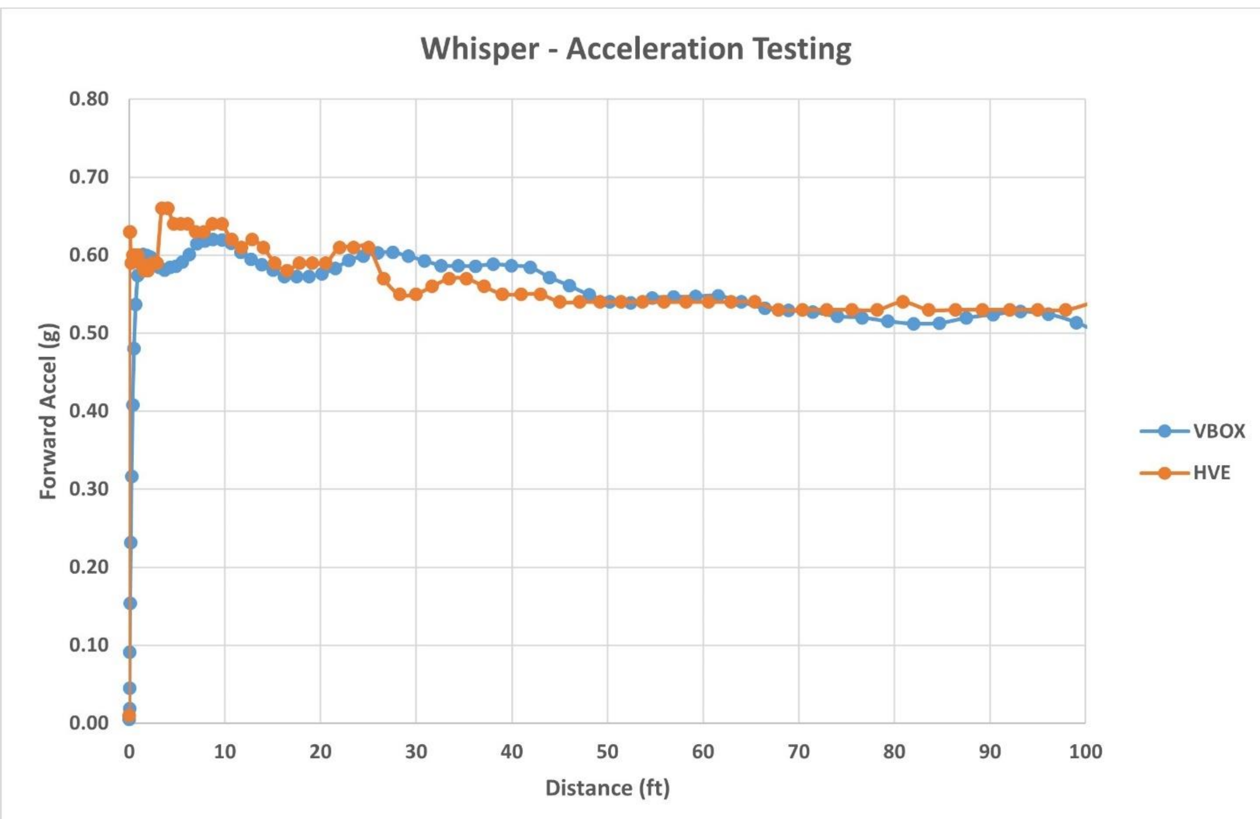

Engage - Acceleration Testing
Speed (mph)
Distance (ft)
VBOX
HVE
0
5
10
15
20
25
30
35
40
45
0
10
20
30
40
50
60
70
80
90
100


Engage - Acceleration Testing
Forward Accel (g)
Distance (ft)
VBOX
HVE
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0
10
20
30
40
50
60
70
80
90
100

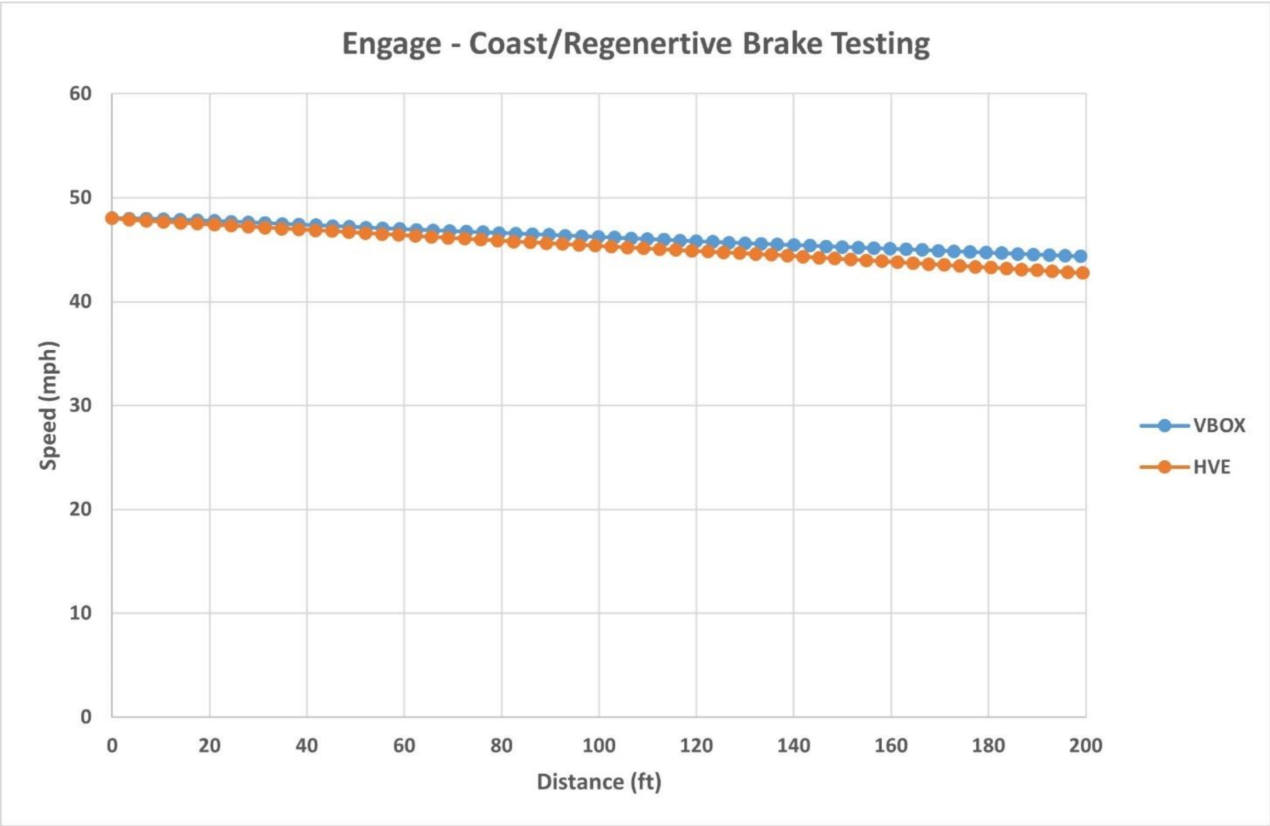

Unbridled - Acceleration Testing
Speed (mph)
0
5
10
15
20
25
30
35
40
45
Distance (ft)
0
10
20
30
40
50
60
70
80
90
100
VBOX
HVE


Unbridled - Acceleration Testing
Forward Accel (g)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
Distance (ft)
0
10
20
30
40
50
60
70
80
90
100
VBOX
HVE

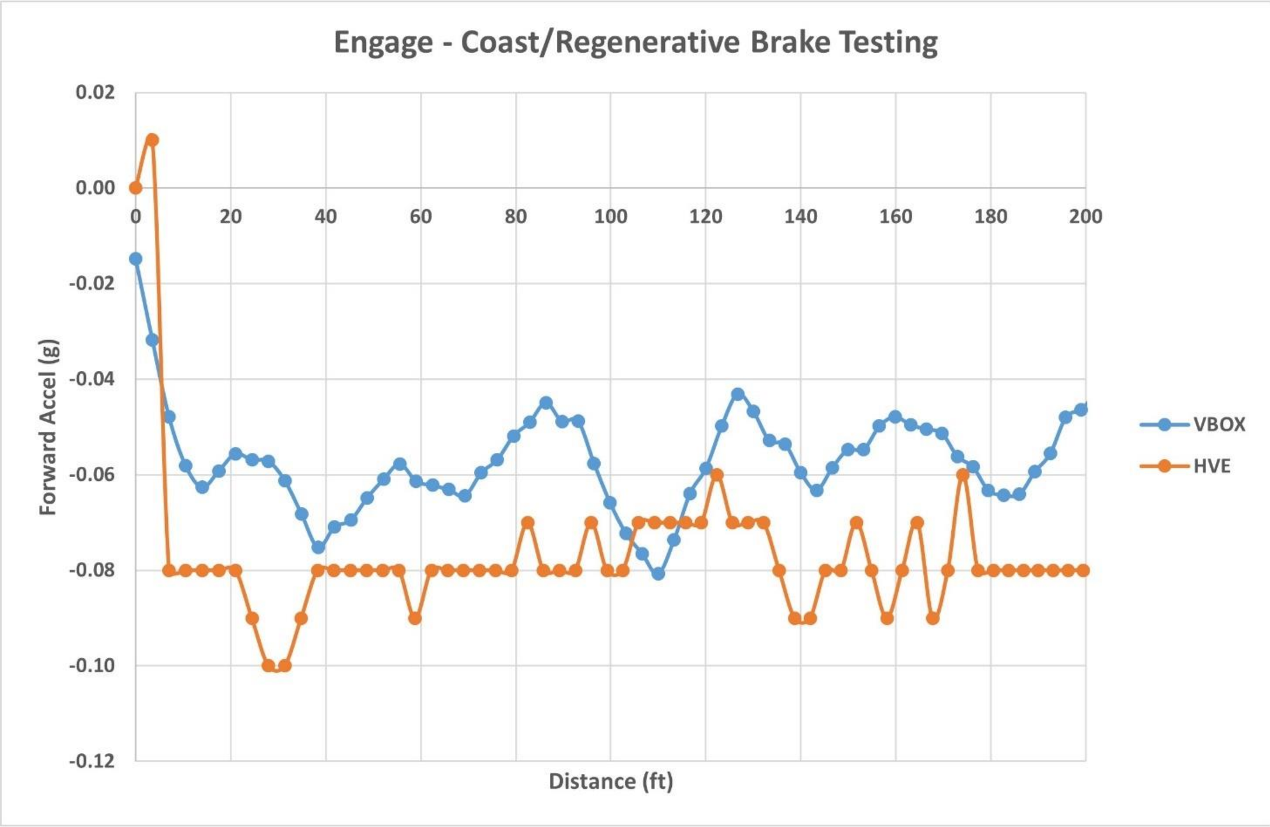

Whisper - Acceleration Testing
Speed (mph)
Distance (ft)
VBOX
HVE
0
5
10
15
20
25
30
35
40
45
0
10
20
30
40
50
60
70
80
90
100


Whisper - Acceleration Testing
Forward Accel (g)
Distance (ft)
VBOX
HVE
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0
10
20
30
40
50
60
70
80
90
100

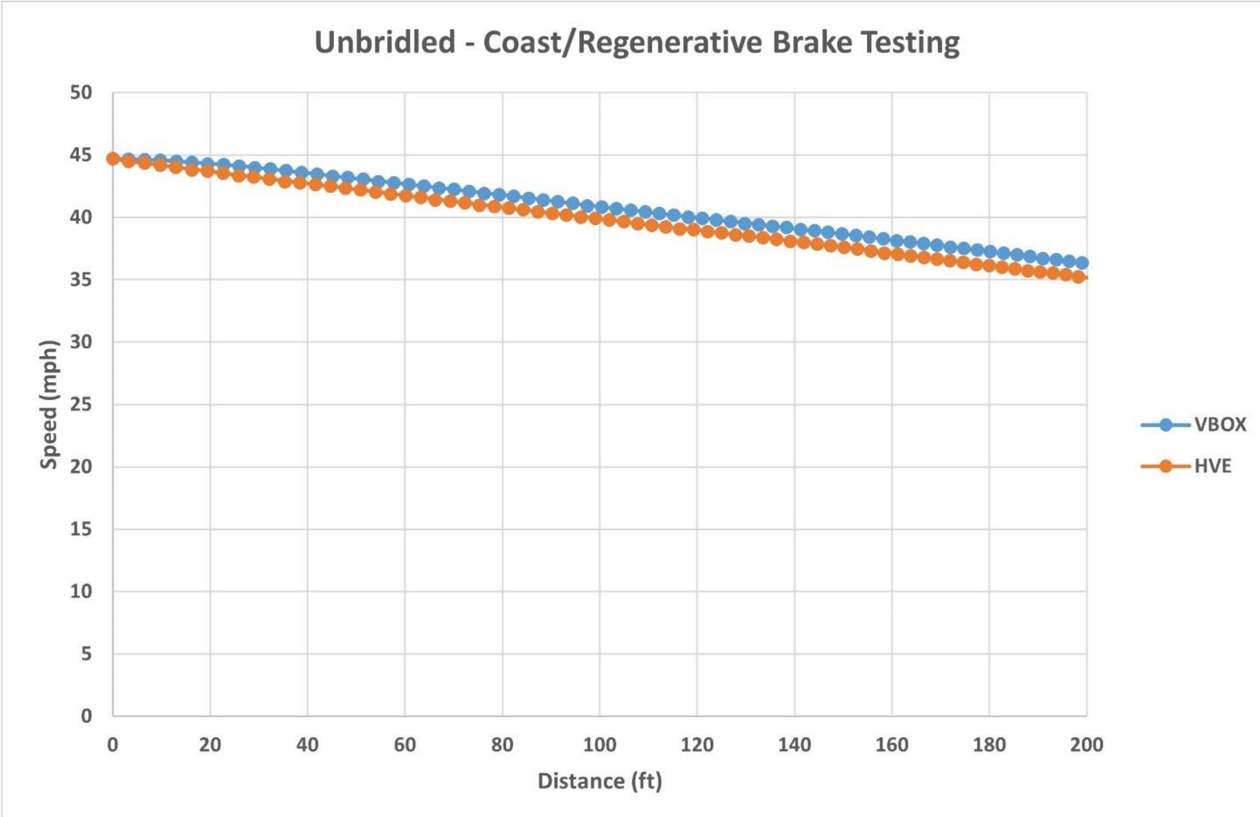
## APPENDIX B



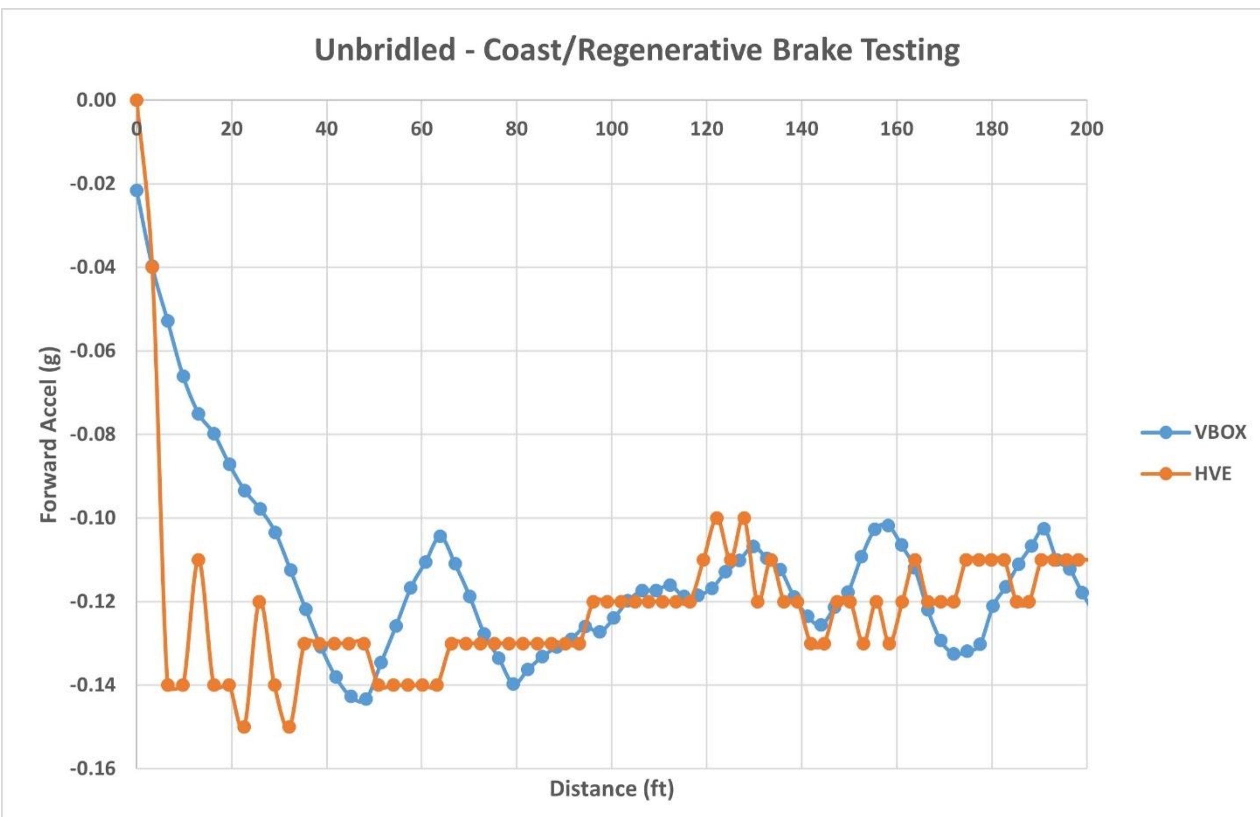
Engage - Coast/Regenertive Brake Testing
60
50
40
30
20
10
0
Speed (mph)
0
20
40
60
80
100
120
140
160
180
200
Distance (ft)
VBOX
HVE

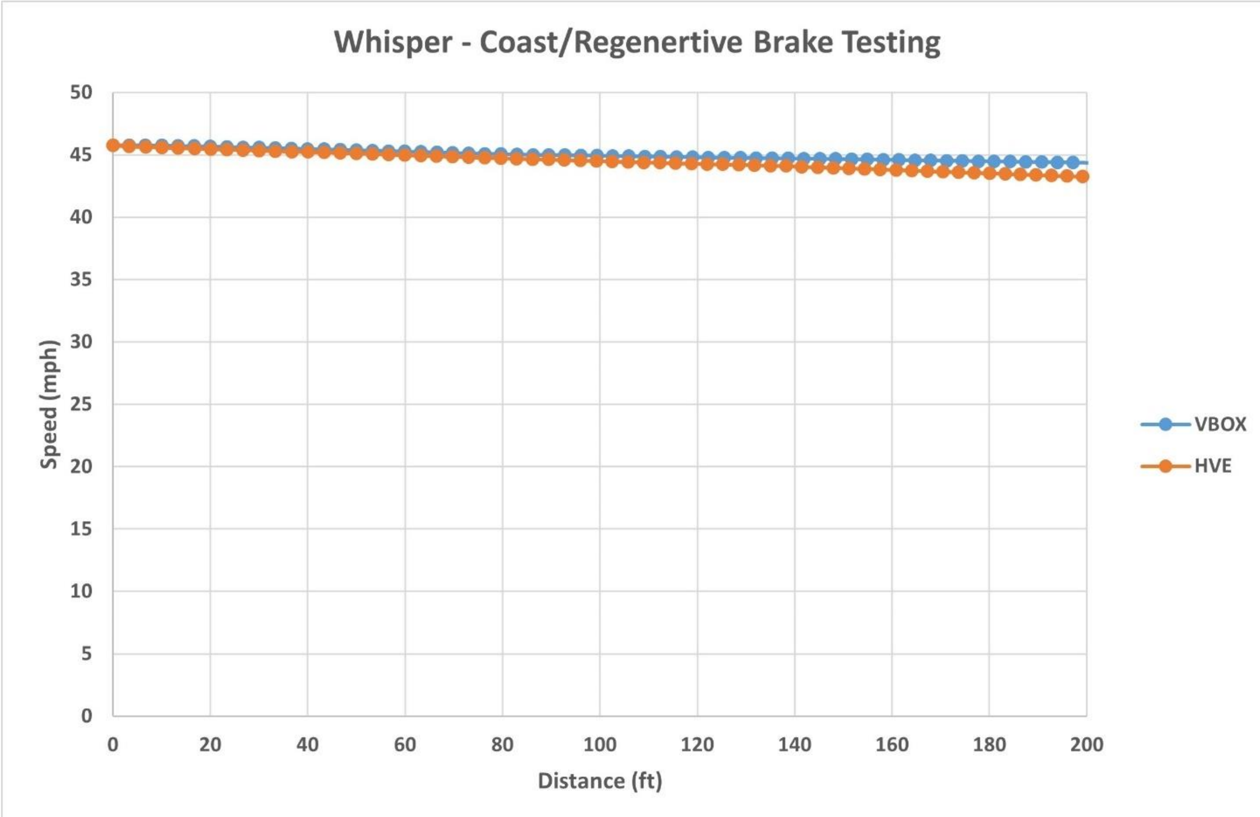
Engage - Coast/Regenerative Brake Testing
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
Forward Accel (g)
0
20
40
60
80
100
120
140
160
180
200
Distance (ft)
VBOX
HVE

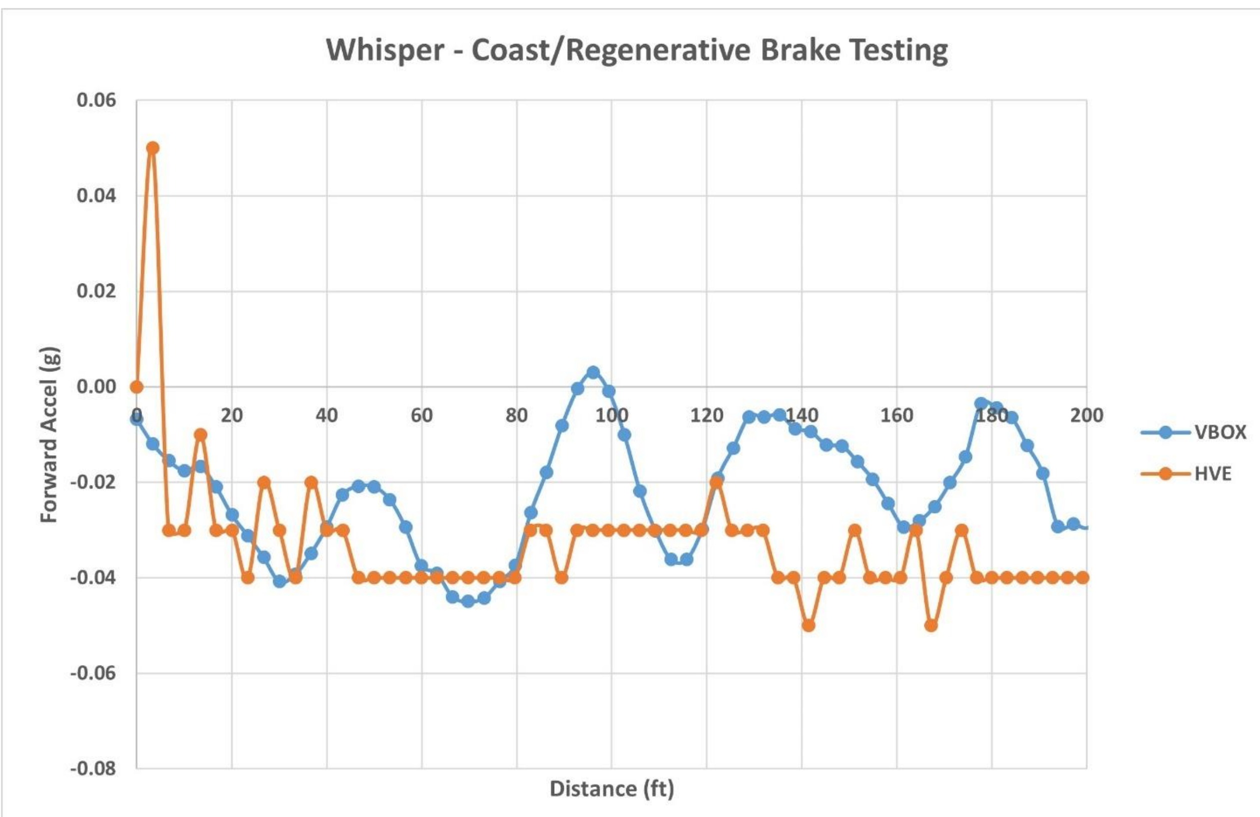


Unbridled - Coast/Regenerative Brake Testing
Speed (mph)
50
45
40
35
30
25
20
15
10
5
0
0 20 40 60 80 100 120 140 160 180 200
Distance (ft)
VBOX
HVE

Unbridled - Coast/Regenerative Brake Testing
Forward Accel (g)
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
0 20 40 60 80 100 120 140 160 180 200
Distance (ft)
VBOX
HVE


Whisper - Coast/Regenertive Brake Testing
Speed (mph)
Distance (ft)
VBOX
HVE
0
5
10
15
20
25
30
35
40
45
50
0
20
40
60
80
100
120
140
160
180
200


Whisper - Coast/Regenerative Brake Testing
Forward Accel (g)
Distance (ft)
VBOX
HVE
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
0
20
40
60
80
100
120
140
160
180
200