HVE-WP-2024-2

Validation of Continuously Variable Transmission (CVT) Equipped Vehicle Acceleration Modeled in HVE

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Abstract

HVE is a powerful tool for accurately reconstructing numerous types of vehicle-related accidents. One of the advantages to utilizing simulation software is the ability to build vehicles based on physically tested or measured parameters and data. The Engineering Dynamics Company (EDC) and Vehiclemetrics vehicle databases combined contain well over 500 vehicles. All of the vehicles currently within HVE are built around a conventional internal combustion engine drivetrain with either an automatic or manual transmission. However, not all contemporary automatic vehicles feature a conventional automatic transmission. Advances in vehicle powertrain technology have led to the development of the continuously variable transmission (CVT), which has a theoretically infinite number of gear ratios between a maximum and minimum. Although this is much different than a standard "N-Speed" automatic, the parameters within HVE can be used to replicate a CVT drivetrain. In this study, six different CVT vehicles were tested with maximum throttle application. Five of the vehicles are included in the EDC or Vehiclemetrics databases. The sixth vehicle, a 2018 Nissan Altima, was not included in either database and was built in HVE using previously established methodologies. This newly built HVE vehicle was then compared to test data to validate the build.

Introduction

A CVT is a transmission type with a maximum and minimum gear ratio, and a theoretically infinite number of gear ratios between. This is different from the "N-Speed" conventional automatic transmission, which has a set number of gears at set ratios. Most CVTs feature a belt-driven system, where the torque from the engine is applied to a driver pully which powers a driven pulley via the belt. The pulley halves are conical and the width between the halves can be varied to change the effective diameter of each pulley. Figure 1 shows a basic overview diagram of a belt driven CVT and illustrates how the ratio is varied. There are other types of CVTs, however the belt driven is the most popular.

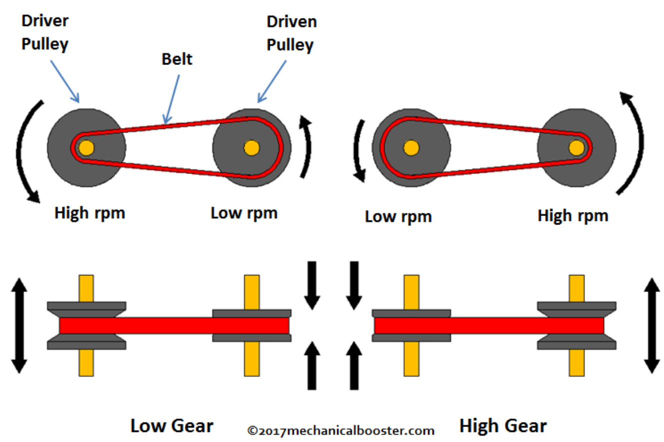


Figure 1. *Belt Driven CVT diagram. Source: 2017mechanicalbooster.com*

The design of these systems is such that the transmission ratio can be anywhere between the fixed high and low ratios dictated by the size of the pulleys/disks. These transmission types are typically tuned to the power curve of the vehicle's engine to obtain efficiency and performance determined by the manufacturer. As there are a theoretically infinite number of gear ratios, the authors aim to validate that inputs can be made to a conventional automatic transmission to create a vehicle in HVE that behaves like a CVT-equipped vehicle. As there are already CVT vehicles included in the EDC and Vehiclemetrics database, this paper aims to validate these vehicles against real world testing, as well as propose and validate a methodology for building a CVT-equipped vehicle.

Vehicle Testing Procedure

The vehicle testing was conducted at SEA's Baltimore facility parking lot, which is asphalt paved. An aerial view of the test location is shown in Figure 2. Testing was only conducted on days when the ground was dry. The area was laser scanned with a FARO Focus^{S} 350 3D laser scanner which generated a point cloud of the testing facility. This point cloud was used to create a surface for use as an environment in HVE, shown in Figure 3.

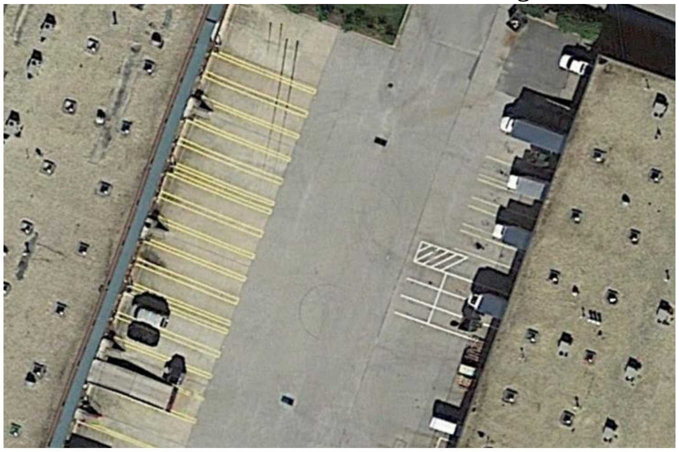


Figure 2. *Aerial view of test location.*

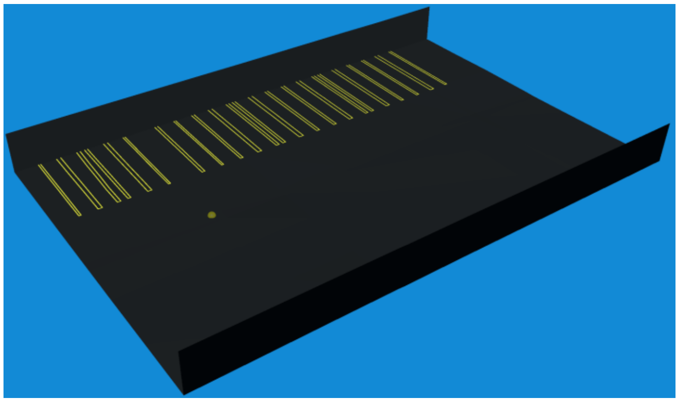


Figure 3. *HVE Surface constructed from 3D laser scan data.*

The tested vehicles were instrumented with a Video VBOX Pro, which samples data at 20 Hz and is capable of different synchronous data channels. The VBOX was used to monitor position and speed via GPS as well as two video feeds, one inside the vehicle and one outside. Figure 4 shows the tested 2018 Nissan Altima outfitted with the Video VBOX data logger. Six different vehicles with CVTs were tested. There were four sedans, a hatchback, and a mid-size SUV tested. All vehicles tested in this paper are belt driven. The tested vehicle catalogue and associated specifications can be found in Table 1. The high and low gear ratios for CVT vehicles are published values.

Year	Make	Model	Trim	CVT Hi	CVT Low	Final Drive	Tire Size
2024	Chevrolet	Malibu	LT	2.645	0.378	5.1	P205/65R16
2018	Honda	Accord	EX-L	2.645	0.405	5.36	225/50R17
2018	Honda	Civic	Sport	2.645	0.405	4.81	235/40ZR18
2018	Nissan	Altima	SV	2.349	0.394	4.828	P215/55R17
2014	Subaru	Impreza	Base	2.37	0.39	3.7	P195/65R15
2017	Subaru	Outback	2.5i	2.37	0.39	4.11	P225/60R18

Table 1. *Tested vehicle specifications.*

Figure 4. *Nissan Altima outfitted with Video VBOX data logger.*

Data was collected for each vehicle at 100% throttle application. The authors positioned the vehicles with the first set of parking lines with the transmission in drive, the operator then switched from full brake application to full throttle application and drove the vehicle at full throttle application for approximately 250 feet. Most applications of full throttle lasted approximately 7 seconds.

HVE Vehicle Creation

Five of the vehicles tested were vehicles included in either the EDC or Vehiclemetrics database. For the Altima, the vehicle was built in HVE using the 2019-2022 Nissan Altima as a base. To build a vehicle in HVE, the authors followed previously established methodologies detailed in Garvey [1], Jadischke [2], and Timbario et. al [3], with the exception of powertrain properties. An additional 150 lbs. was added to the weight of all vehicles for the weight of the single occupant during testing.

<u>Gear Ratios</u>

To begin modeling the HVE vehicle transmission as a CVT in the vehicle editor, the authors set the vehicle as an automatic transmission. The high and low CVT ratios for each transmission were determined via published values. It is recommended by the authors to cross reference the transmission ratio values, as commonly used published resources may be incorrect. Manufacturer websites and/or manufacturer data specific to the transmission in the vehicle are good resources to verify the high and low CVT ratio. In this research, a 6-speed automatic transmission was used when modeling a CVT, unless the vehicle in HVE was already input as a 12-speed, then it was analyzed in its stock configuration. The gear ratios were determined utilizing the published high and low ratios and fitting the interpolated intermediate values with a logarithmic curve. This logarithmic approximation can be used for any number of transmission speeds, not just a 6-speed as was done in this paper. A logarithmic curve was used by the authors as many conventional automatic transmission vehicles generally follow this trend. Figure 6 shows the gear ratios of three automatic-transmission-equipped sedans plotted and fitted with a logarithmic curve. A 2000-2003 Acura 3.2TL, 2000-2011 Ford Focus, and a 2012-2014 Toyota Camry LE were selected as examples. Of the three vehicles selected, the R^2 values for the curves are all higher than 0.979. Figure 7 shows the hypothetical curve for a 2018 Nissan Altima based on the high and low CVT ratio fitted with a logarithmic curve.

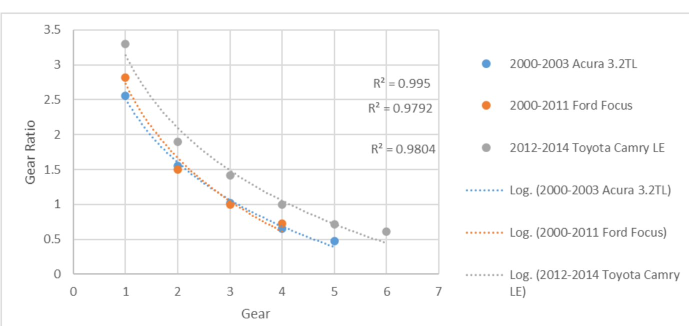


Figure 6. *Three conventional automatic transmission vehicle gear ratios fitted with logarithmic curves.*

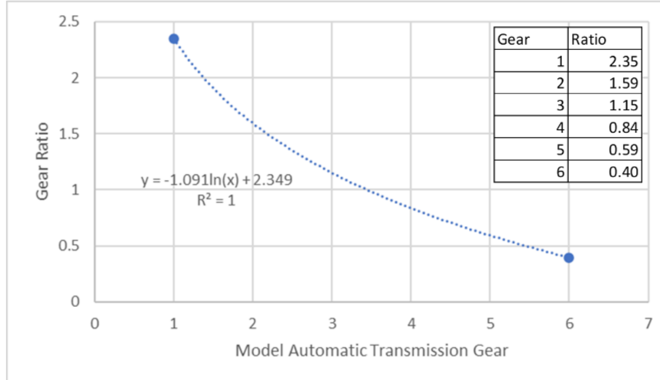


Figure 7. *2018 Nissan Altima theoretical logarithmic gear ratios.*

EDC and Vehiclemetrics prefer to use all 12 gear ratios available in HVE's transmission model. Ratios 1 and 12 are taken directly from the CVT's published low and high values, while the other 10 ratios are calculated with equations derived from a 6th order polynomial shown in Appendix C.

<u>Wide Open Throttle Curve</u>

Online resources and manufacturer specifications are available to determine horsepower (HP) and torque curves, which can be modeled in HVE. Figure 8 is an example HP and torque curve for a 2018 Nissan Altima. The published HP and torque curves used by the authors are simulated results based on factory data inputs. The HP and torque data can be entered and modeled in the HVE engine modeler table.

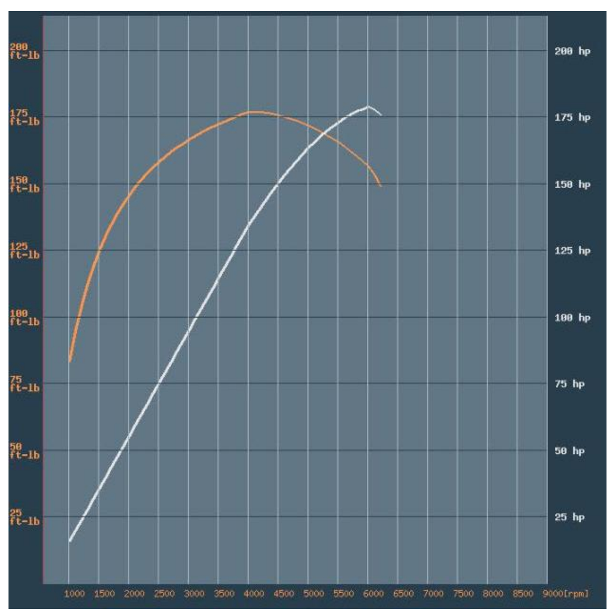


Figure 8. *2018 Nissan Altima HP and torque curve from automobile-catalogue.com.*

Closed Throttle Curve

To establish closed throttle curves, follow previously established methodology detailed in Garvey [1] to calculate the closed throttle curve values, and then enter them in the HVE engine modeler table. Coast down speeds were not validated and are outside the scope of this paper.

HVE Simulation Results

All six vehicles were simulated in HVE, and the speed curves were compared to the Video VBOX test data. Throttle pedal application is defined as percent of wide-open-throttle (%WOT) in HVE, which can be different from a vehicle manufacturer's definition of applied throttle in the vehicle. As such, the two conditions where the throttle pedal application can be easily evaluated are at 100% WOT (fully open) and 0% WOT (fully closed). Thus, all vehicles were simulated at maximum throttle application. The gear ratios for five of the vehicles that were from the EDC or Vehiclemetrics databases were left unchanged. The Nissan Altima used the logarithmic gear curve based on its high and low CVT ratio. The gear ratios tested are shown below in Appendix A. Table 1 shows the root mean square error (RMSE) values, as well as maximum absolute error (MAE) for vehicle speed. RMSE was computed for all common timesteps, and MAE was computed as the greatest difference between speed values between the simulation and test data. The maximum speed values for both the test data and the HVE simulation are also reported. The HVE stock curves plotted against VBOX data can be found in Appendix B.

Vehicle	RMSE (mph)	MAE (mph)	Max VBOX Speed (mph)	Max HVE Speed (mph)
Chevrolet Malibu	1.4	2.7	48.64	47.76
Honda Accord	1.1	2.0	50.82	50.10
Honda Civic	1.2	1.8	43.02	42.36
Nissan Altima	2.3	3.8	47.31	49.39
Subaru Impreza	7.8	10.0	40.53	51.70
Subaru Outback	10.0	12.4	44.94	57.33

Table 1. *Stock EDC and Vehiclemetrics database vehicles speed error values and max speeds.*

The Malibu, Civic, Accord, and Nissan speed curves all show reasonably good agreement. The Malibu has an initial over approximation, but after 3 seconds, the speed profiles overlay almost identically, which is shown in Appendix B. This could be related to the vehicle not giving the driver the power requested as a safety feature, or turbo delay. The Chevrolet Malibu has a high MAE due to this initial speed over approximation. The built Nissan Altima is overapproximated in the simulation by a noticeable degree. Both tested Honda vehicles show excellent agreement with their simulated counterparts.

The EDC approach of using a 6^{th} order polynomial was also simulated. The results of this methodology are functionally identical to the logarithmic curve methodology tested in this paper.

It was noted that the Vehiclemetrics database has different high and low ratio for the Malibu, as well as different values for the rear differential. This is true for the tested 2024 Malibu which is the same generation as the 2016-2022 model years listed in the database. These values were updated in a new simulation and the error was analyzed. Both the HVE stock and the updated transmission ratio curves are shown in Appendix B. The updated RMSE and MAE are shown in Table 2. The correct gear ratio and differential ratio raises the RMSE by 0.2 mph but decreases the MAE by 0.2 mph. The low difference between the two simulations is likely a result of the gear ratios being overapproximated, but the final drive ratio was underapproximated. These values appear to balance, and both show agreement with the VBOX speed.

The Subaru vehicles are both well over approximated by the initial HVE simulation. The reason for this is the 2012-2016 Subaru Impreza was one of a few CVT transmissions EDC built before implementing the 6^{th} order polynomial method back in 2019. Back then, EDC used the published Paddle Shift ratios as the CVT transmission ratios. As for the 2015-2019 Subaru Outback, this used the current 12-spd method, but the published min and max CVT ratios EDC used were different from what the authors found. The authors did extensive research on the Subaru Lineartronic Transmission, which is installed on both tested vehicles. The high and low ratios of the transmission were found to be between 2.37 and 0.39 [4]. HVE currently has the 2012-2016 Subaru Impreza gear ratios listed between 3.58 and 0.57 and has the 2015-2019 Subaru Outback gear ratios listed between 3.58 and 0.62. The gear ratios were updated using the researched high and low ratios and subsequently calculated by using the logarithmic gear approximation described earlier. The RMSE and MAE using these gear ratios are shown in Table 2, and the speed curves are shown in Appendix B.

Vehicle	RMSE (mph)	MAE (mph)	Max VBOX Speed (mph)	Max HVE Speed (mph)
Chevrolet Malibu	1.6	2.5	48.64	47.11
Subaru Impreza	0.8	1.8	40.53	42.67
Subaru Outback	1.5	3.7	44.94	48.66

Table 2. *Chevrolet Malibu and Subaru vehicles with updated log transmission ratio speed error values and max speeds.*

After the implemented changes, the Subaru vehicles show a much lower RMSE and MAE as compared to the stock HVE vehicles. Both RMSE values are less than 1.5 mph.

Drivetrain Modifications

In an effort to even further reduce the error values, the authors explored modifications that could be further made to the drivetrain parameters in HVE.

Shift RPM

EDC uses formulae to determine the high and low shift points for an automatic engine, which are shown below in equations 1 and 2.

1. $MinShift = 0.2 * WOTmaxRPM + 0.8 * WOTminRPM$
2. $MaxShift = 0.8 * WOTmaxRPM + 0.2 * WOTminRPM$

When building a vehicle in HVE the resultant shift RPMs will auto populate based on the formulas used above. These values can be changed to a value that the user desires without impacting the WOT table. The values to be changed are shown below in Figure 9.

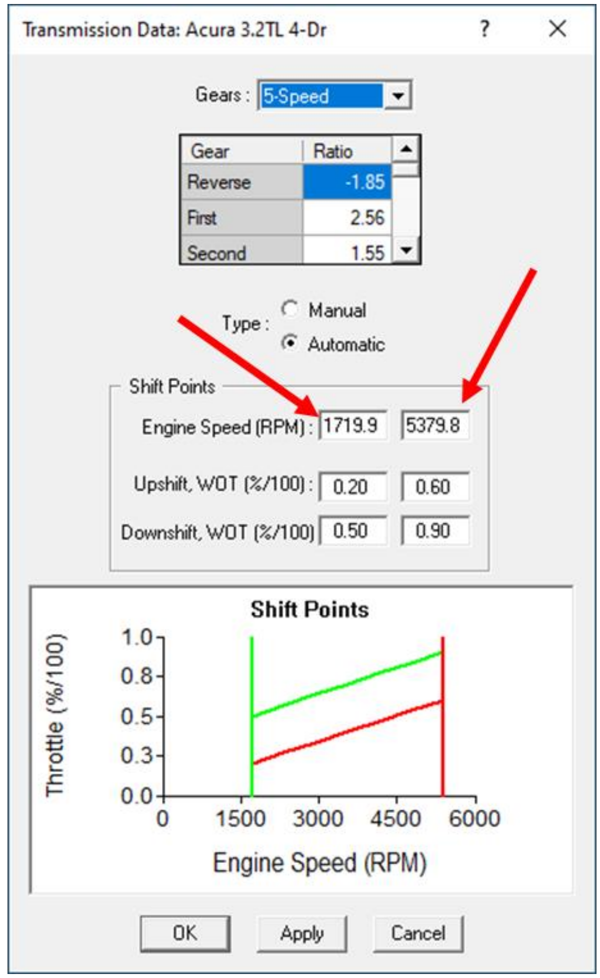


Figure 9. 2000 *Acura 3.2TL engine shift points.*

Setting the upshift RPM lower will allow the vehicle to shift into a higher gear more quickly, which results in a quicker reduction in slope of the speed curve when accelerating from a stop. An example of this is shown in Figure 10 with a 2000 Acura 3.2TL. The blue curve is the stock vehicle in HVE, with an upshift RPM of 5379.8 RPM. The orange curve is the stock vehicle with its upshift point set at 4500 RPM. The grey curve is the stock vehicle with its upshift point set at 4000 RPM. This example serves only to illustrate HVE engine properties and is not related to the test data. In the example case, the stock vehicle accelerates to 44.6 mph at 6.5 s, the 4500 RPM vehicle accelerates to 41.2 mph, and the 4000 RPM vehicle accelerates to 39.1 mph.

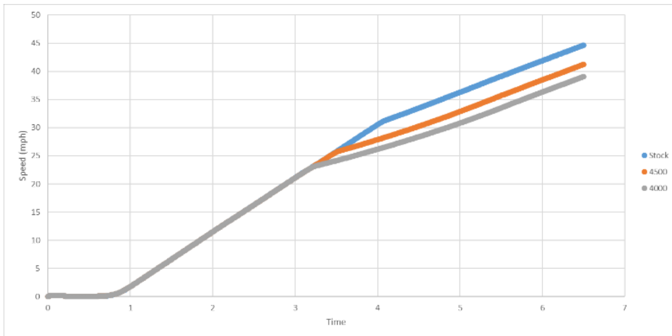


Figure 10. 2000 *Acura 3.2TL Speed vs. Time curve for different upshift RPMs.*

Upshift Modifications to Tested Vehicles

The authors hypothesized that by using EDC's equation with the 2nd highest RPM listed in the powertrain table, that the error values in the simulation would decrease. For the two tested Subaru vehicles, the maximum horsepower value is at a high RPM. This leads the maximum RPM in the table to be on the order of 7000. When the EDC equation for upshift RPM is used to calculate the upshift point for the Subaru vehicles, the value is at a very high value at approximately 6000 RPM. This is an unrealistic upshift max for everyday driving, and likely leads to over approximation of speed and acceleration values as the vehicle will stay in a lower gear for longer. For the Nissan Altima, which had a manually entered curve, the second highest value was on the order of 5000 RPM, which was consistent with other database vehicles. The error values shown in Table 3 have both the updated transmission ratio for Subaru vehicles and the Malibu as well as the upshift RPMs lowered applied to all vehicles as described above. The updated speed curves are shown in Appendix B.

Vehicle	RMSE (mph)	MAE (mph)	Max VBOX Speed (mph)	Max HVE Speed (mph)
Chevrolet Malibu	2.0	3.2	48.64	45.98
Honda Accord	1.5	3.6	50.82	48.22
Honda Civic	1.2	1.8	43.02	41.71
Nissan Altima	1.6	3.1	47.31	47.21
Subaru Impreza	0.8	1.7	40.53	42.01
Subaru Outback	0.9	1.9	44.94	45.65

Table 3. *All tested vehicles with updated log transmission ratio and lowered upshift RPM speed error values and max speeds.*

These modifications had positive impacts on the Nissan Altima, Subaru Impreza, and Subaru Outback. RMSE for the Subaru Outback dropped by 0.6 mph, and the Nissan Altima RMSE dropped by 0.7 mph. The RMSE for the Subaru Impreza was unchanged, but did drop the MAE by 0.1 mph. These modifications had negative effects on the Chevrolet Malibu and Honda Accord. The Chevrolet Malibu RMSE increased by 0.4 mph. The Honda Accord RMSE increased by 0.4 mph, and the MAE notably increased by 1.6 mph. The Honda Civic was slightly negatively affected. The Nissan Altima maximum speed values are separated by only 0.1 mph.

When the EDC methodology of the 12-speed, 6th order polynomial gear ratio determination is simulated with the RPM shift, the vehicle shifts into a higher gear at approximately the same time in both cases, but the ratio change is not as significant using the 12-speed, which results in a higher speed at the end of the simulation. The vehicles that the RPM shift positively impacts show less agreement when the EDC methodology is used as compared to the 6-speed logarithmic gear ratio method.

Overall, the upshift modification positively affected half of the tested vehicles. When modeling CVT acceleration the authors recommend taking into account the RPM vs horsepower table and taking note of the last RPM value. If this value is very high compared to other vehicles, consider applying this shift. More testing needs to be done to determine conclusively when this shift should be applied.

Conclusions

This paper validates five of the CVT-equipped sedan vehicles included in the EDC and Vehiclemetrics database within HVE, and one vehicle built in HVE using previously established methodologies. Updates to reflect powertrain properties were made to the two tested Subaru vehicles and the Chevrolet Malibu based on researched high and low CVT ratios. A new method for determining gear ratios for the model CVT-equipped HVE vehicle using a logarithmic curve was detailed and validated. The logarithmic curve uses the two known ratios of the CVT and approximates the other gear ratios using the logarithmic function. This logarithmic gear approach can be used to approximate transmissions with any number of set gears. All six vehicles were modeled in HVE and had speed curves plotted against VBOX speed data. All vehicles had reasonable agreement with test data. The authors describe an RPM shift that can be used to increase accuracy for three of the tested vehicles.

Special Thanks

A special thanks to Thomas Timbario for his contributions to this research.

References

1. Garvey, J.T., *Building Vehicles for HVE*, WP2006-6, Engineering Dynamics Corporation, Beaverton, OR, 2006.
2. Jadischke, R., McCarthy, J., McCarthy, J., and Ellis, D., *An Introduction to the Vehiclemetrics HVE Vehicle Database*, WP2012-2, Engineering Dynamics Corporation, Beaverton, OR, 2012.
3. Timbario, T., Swanson, J., Wahba, R., Sheldon, S., Stoner, J., *Building and Validation of a Battery Electric Vehicle (BEV) for HVE,* WP-2023-1, Engineering Dynamics Corporation, Beaverton, OR, 2023.
4. Souza, M., *Subaru Lineartronic CVT Introduction,* Lineartronic CVT Webinar, Automatic Transmission Rebuilders Association, 2015.

APPENDIX A – Tested Vehicle Gear Ratios

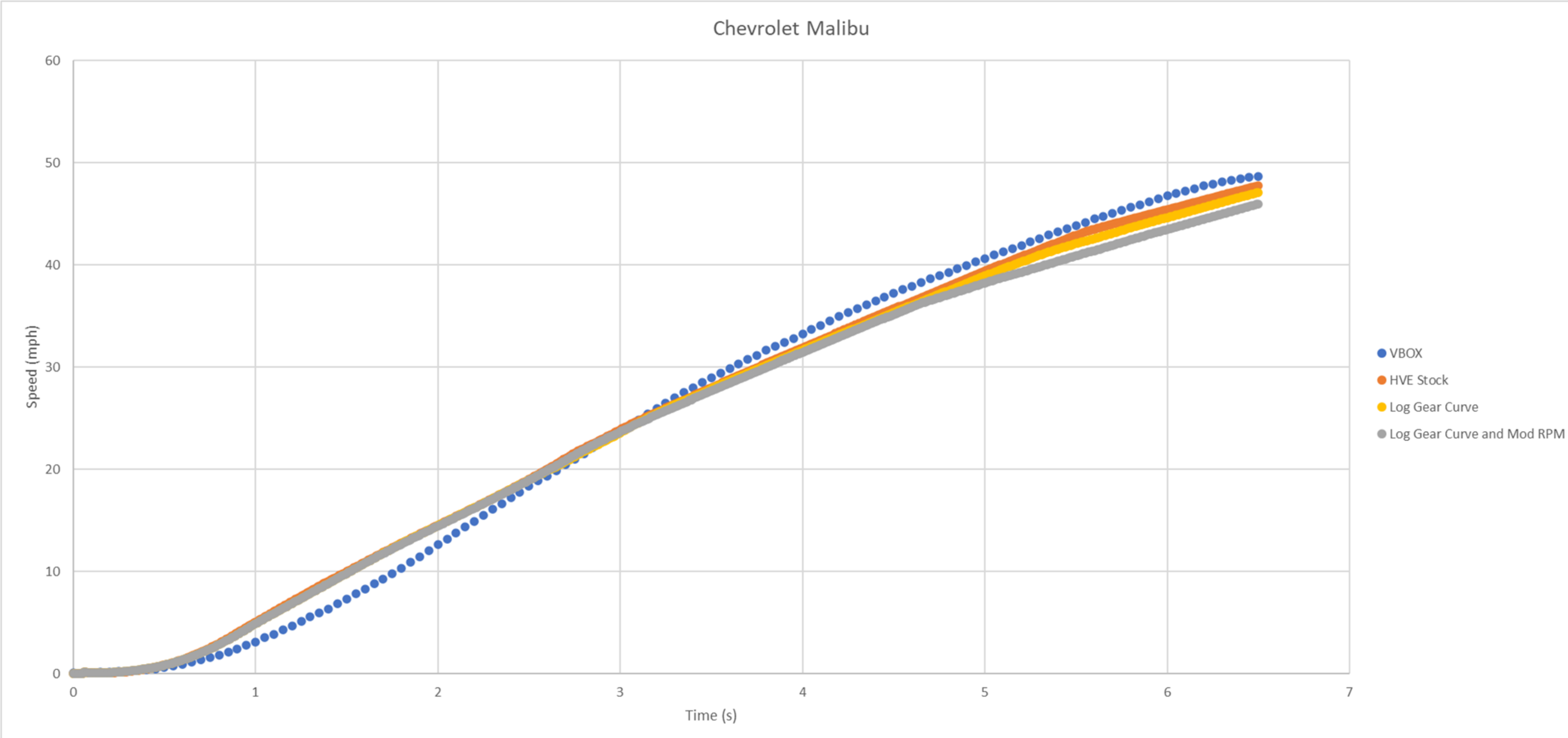
Prior to Transmission Update

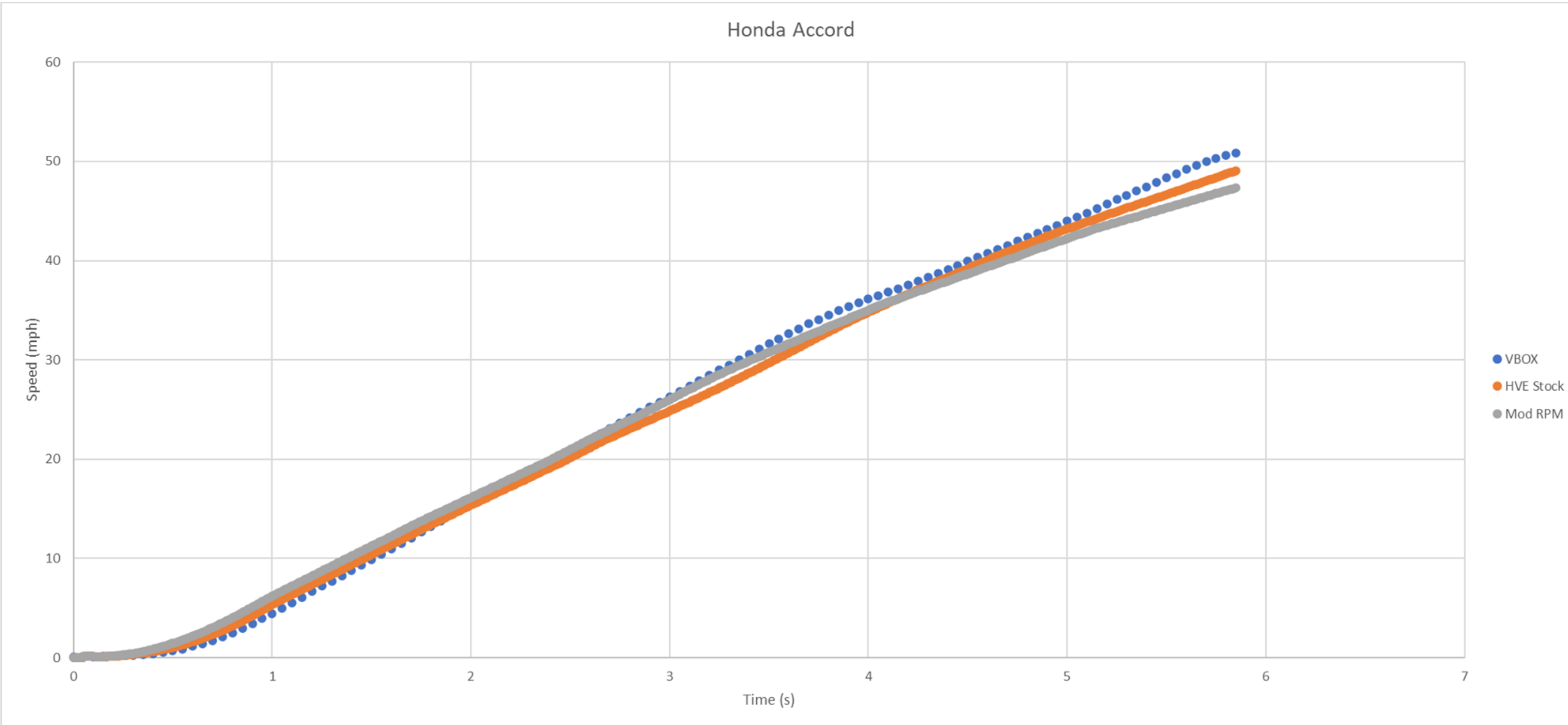
	1	2	3	4	5	6	7	8	9	10	11	12
Chevrolet Malibu	4.58	2.96	1.91	1.45	1	0.75						
Honda Accord	2.65	2.06	1.67	1.39	1.18	1	0.85	0.72	0.62	0.54	0.48	0.41
Honda Civic	2.65	2.06	1.67	1.39	1.18	1	0.85	0.72	0.62	0.54	0.48	0.41
Nissan Altima	2.35	1.59	1.15	0.84	0.59	0.4						
Subaru Impreza	3.58	2.26	1.66	1.21	0.89	0.57						
Subaru Outback	3.48	2.81	2.3	1.93	1.64	1.41	1.21	1.04	0.9	0.8	0.71	0.62

After Transmission Update

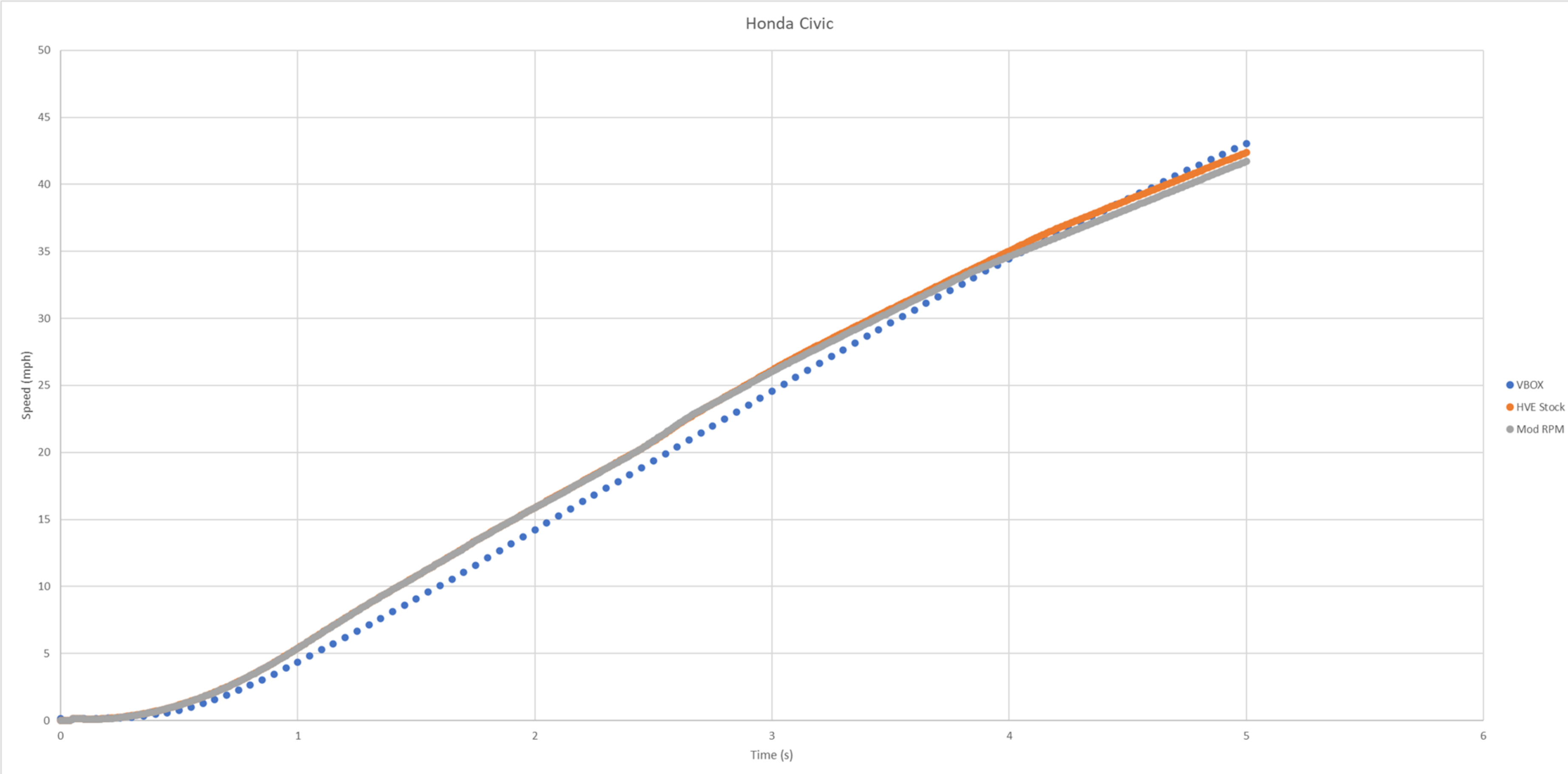
	1	2	3	4	5	6	7	8	9	10	11	12
Chevrolet Malibu	2.65	1.77	1.26	0.89	0.61	0.38						
Honda Accord	2.65	2.06	1.67	1.39	1.18	1	0.85	0.72	0.62	0.54	0.48	0.41
Honda Civic	2.65	2.06	1.67	1.39	1.18	1	0.85	0.72	0.62	0.54	0.48	0.41
Nissan Altima	2.35	1.59	1.15	0.84	0.59	0.4						
Subaru Impreza	2.37	1.6	1.16	0.84	0.59	0.39						
Subaru Outback	2.37	1.6	1.16	0.84	0.59	0.39						

APPENDIX B – HVE Vehicles Compared to VBOX Test Data

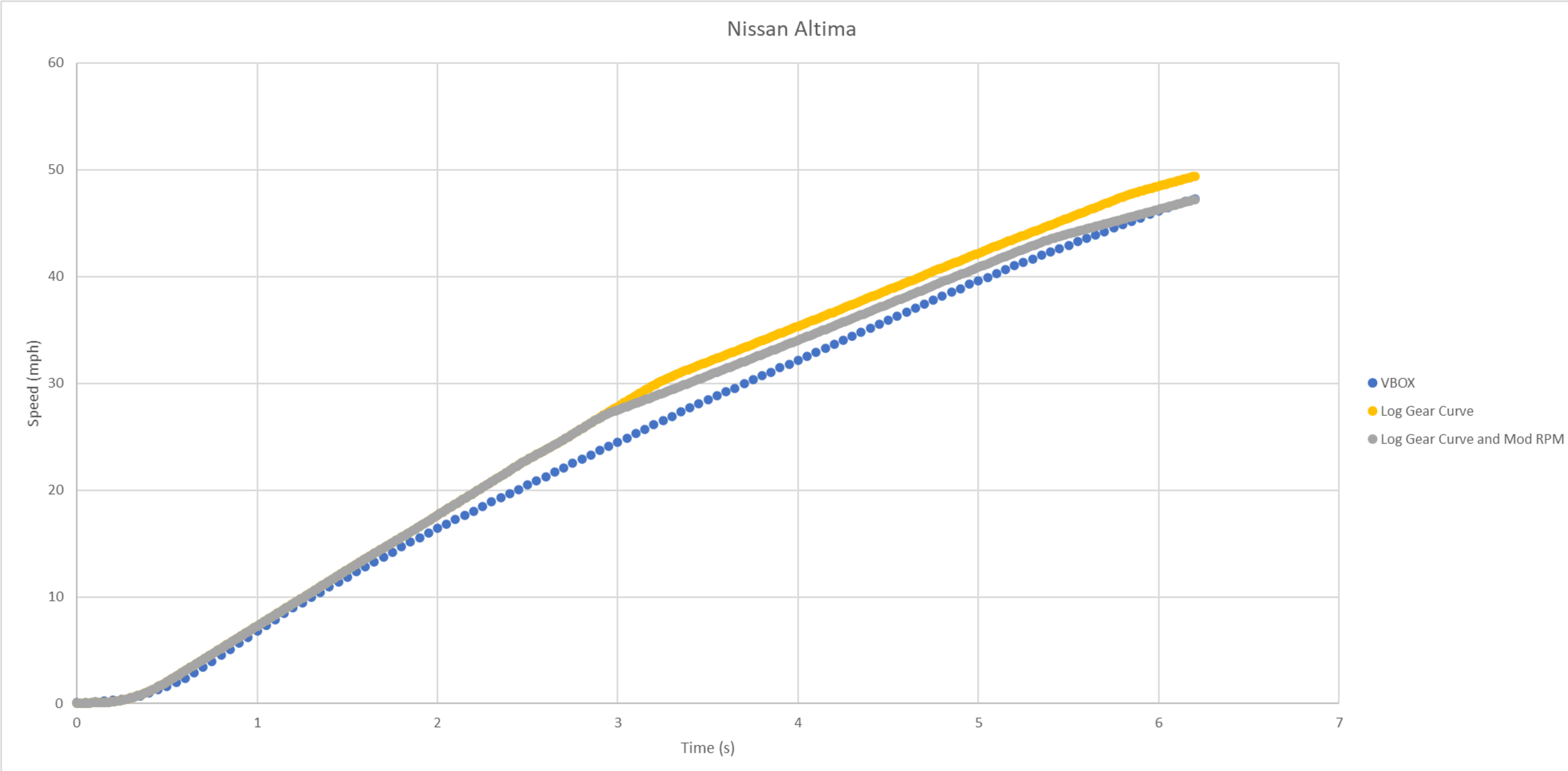


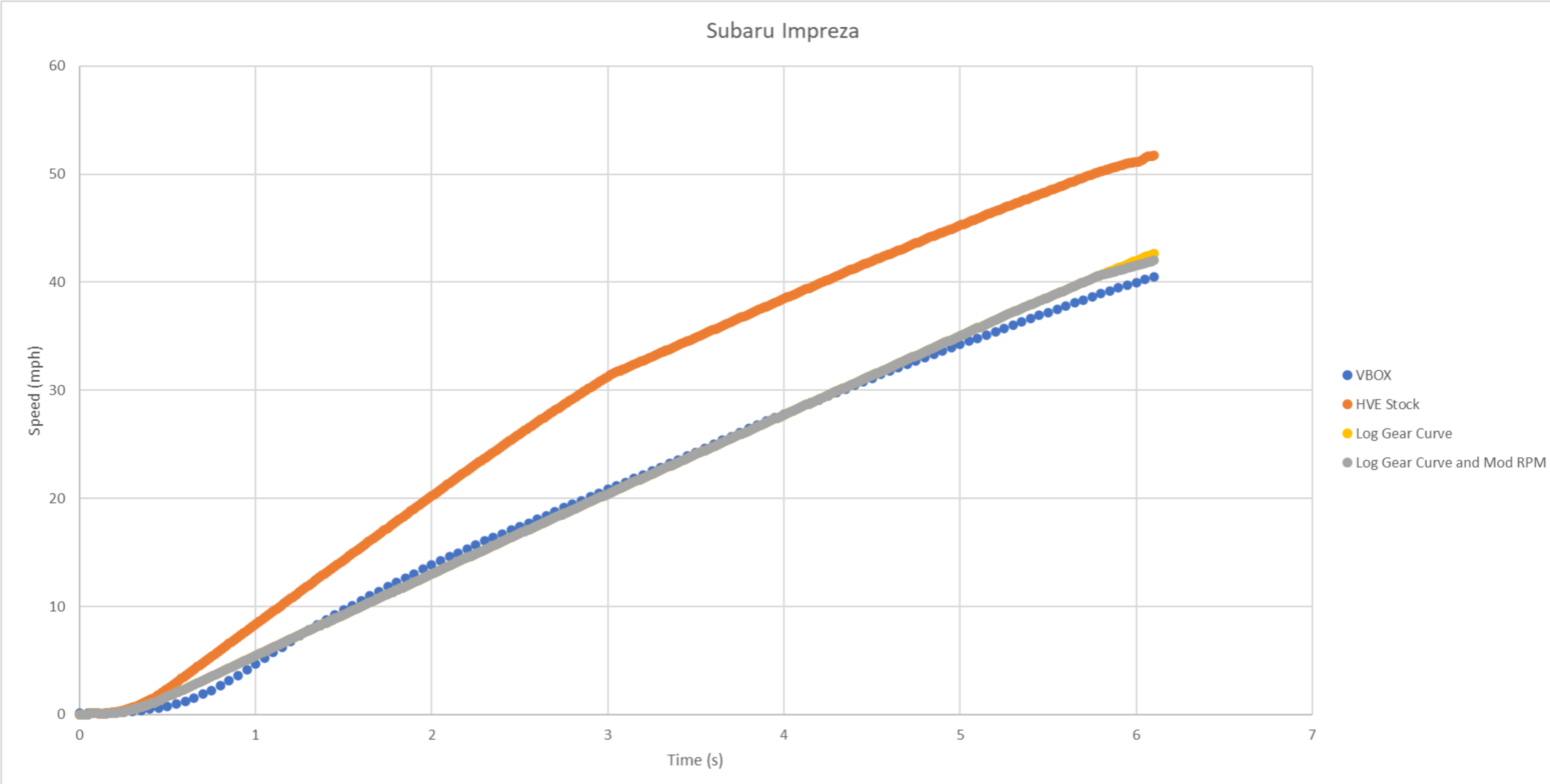


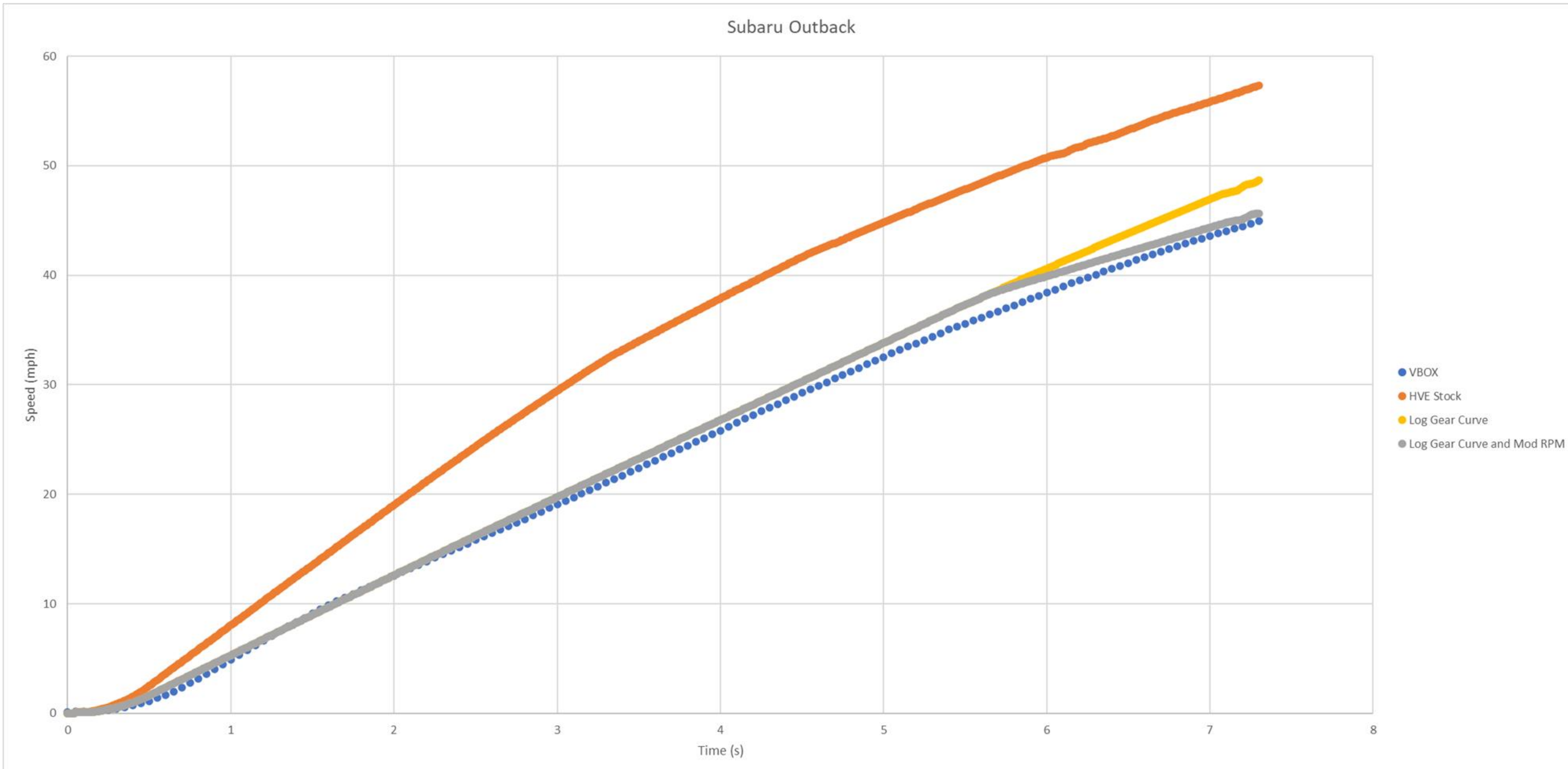
Honda Accord
Speed (mph)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
Time (s)
VBOX
HVE Stock
Mod RPM



Honda Civic
Speed (mph)
Time (s)
VBOX
HVE Stock
Mod RPM


Nissan Altima
Speed (mph)
Time (s)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
VBOX
Log Gear Curve
Log Gear Curve and Mod RPM


Subaru Impreza
Speed (mph)
Time (s)
0
10
20
30
40
50
60
0
1
2
3
4
5
6
7
VBOX
HVE Stock
Log Gear Curve
Log Gear Curve and Mod RPM


Subaru Outback
Speed (mph)
Time (s)
0
10
20
30
40
50
60
0
1
2
3
4
5
6
7
8
VBOX
HVE Stock
Log Gear Curve
Log Gear Curve and Mod RPM

APPENDIX C – EDC and Vehiclemetrics' CVT Ratio Calculations

A = Published High CVT Ratio B = Published Low CVT Ratio

Gear 1 = Published High Ratio

Gear 2 = (A – B) x 0.741 + B

Gear 3 = (A – B) x 0.5661 + B

Gear 4 = (A – B) x 0.4416 + B

Gear 5 = (A – B) x 0.3458 + B

Gear 6 = (A – B) x 0.2667 + B

Gear 7 = (A – B) x 0.199 + B

Gear 8 = (A – B) x 0.1418 + B

Gear 9 = (A – B) x 0.0956 + B

Gear 10 = (A – B) x 0.0601 + B

Gear 11 = (A – B) x 0.0314 + B

Gear 12 = Published Low Ratio