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Testing and Modeling of Engine Idle Creep in Conventional Automatic-Equipped Vehicles

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Abstract

For the accident reconstructionist, determining speeds at impact for the vehicles involved is an important factor in any reconstruction. In low-speed collisions where injury considerations are often important, traditional damage-based methods may be ineffective in quantifying the severity of the impact due to a lack of defined vehicle crush damage. One such scenario might entail a stopped target vehicle and a bullet vehicle stopped initially behind the target vehicle. The foot of the driver of the bullet vehicle ceases applying brake pedal pressure, allowing the bullet vehicle to move forward at idle engine speed without the driver applying accelerator pedal pressure. As a result, the target vehicle "creeps" forward and strikes the bullet vehicle resulting in no visible crush damage to either vehicle. Nine vehicles with conventional automatic transmissions were tested, which included sedans, sport utility vehicles (SUVs), and vans. These vehicles were allowed to idle with the brake pedals released. Acceleration, speed, and distance data were collected for multiple vehicles runs in both forward and reverse directions over level ground. The data resulting from this study was then used to determine what modifications are necessary to the HVE vehicle drivetrain model to successfully model the idle creep phenomenon.

Introduction

Unlike manual transmission-equipped vehicles that employ a clutch to completely disconnect the rotating engine from the transmission, vehicles equipped with an automatic transmission instead use a fluid coupling known as a torque converter. At idle speeds when a vehicle is stopped, a small amount of torque is passed from the rotating engine to the impeller/pump of the torque converter. The spinning impeller then moves fluid to the fins of a turbine which is connected to the input shaft of the transmission. This in turn transmits a torque to the transmission. To keep the vehicle from moving, only a light amount of brake pedal application is necessary. Applying accelerator pedal pressure, which in turn causes the engine to rotate faster and therefore pass more torque to the torque convertor, would require additional brake pedal application. Removing all brake and accelerator pedal pressure would then result in the vehicle creeping forward.

Idle speed creep testing has been well documented in the past. Rast et al. [1] conducted testing on 14 mostly 1990s vintage passenger cars, SUVs, and vans. Testing was performed in both forward and reverse directions on level ground. Peak and average accelerations and maximum vehicle speeds were recorded using a G-Analyst and radar gun, respectively. Results from that testing showed a mean average acceleration of 0.029 g with a standard deviation of 0.009 g and a peak of 0.051 g. Mean maximum forward speed was 3.5 mph, ranging from 3-4 mph; mean maximum reverse speed was 3.25 mph and ranged from 2-5 mph.

Reust [2] presented on 18 vehicles tested on a level surface. Results indicate average accelerations ranging from 0.025-0.029 g over the first 10 ft with maximum speeds recorded between 3-6 mph after approximately 30 ft.

Randles et al. [3] conducted testing on 23 vehicles ranging in model years from 1991 to 2014 and included sedans, SUVs, and pick-up trucks on three different surfaces: level, "medium" sloped, and "high" sloped. Results were recorded with a VBOX III and filtered with a 6th order Butterworth filter. Level surface testing produced an average speed of 5.0 mph with a mean standard deviation of 1.48 mph for sedans, and 4.71 mph with a mean standard deviation of 0.75 mph for SUVs and pick-up

trucks after 100-400 ft of travel. Sedan and SUV/pick-up accelerations were modeled for the first 20 ft of travel and plotted; direct values were not given in the study. The charts from this research indicate a mean peak acceleration of approximately 0.05 g for sedans and approximately 0.043 g for SUVs/pick-up trucks.

Theoretical Background

One well-known method for determining vehicle maximum speed for a given gear is through a sawtooth analysis. This method produces a vehicle speed in mph at a given engine speed if the installed tire size, transmission ratio, and final drive ratio are known with the following equation:

$$V = \frac{(R) \times \left(\frac{60\ min}{1\ hr}\right)}{(T_R \times R_T \times R_A)} \qquad (1)$$

where R is the engine speed in rpm, T_R is the tire revolutions per mile, R_T is the transmission ratio, and R_A is the final drive ratio. Thus, a theoretical maximum speed can be calculated for first and reverse gears at idle speed. However, acceleration rates or distance traveled to reach top speed cannot be gleaned from Equation 1.

Vehicle Testing Procedure

Vehicle testing in first gear and reverse gear was conducted in a limited access business park on an asphalt-paved, dry surface. An aerial of the location showing the direction of vehicle travel is shown in Figure 1. 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 2).

Each vehicle 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 engine speed and vehicle speed. Figure 3 shows a test vehicle equipped with the various instrumentation devices.

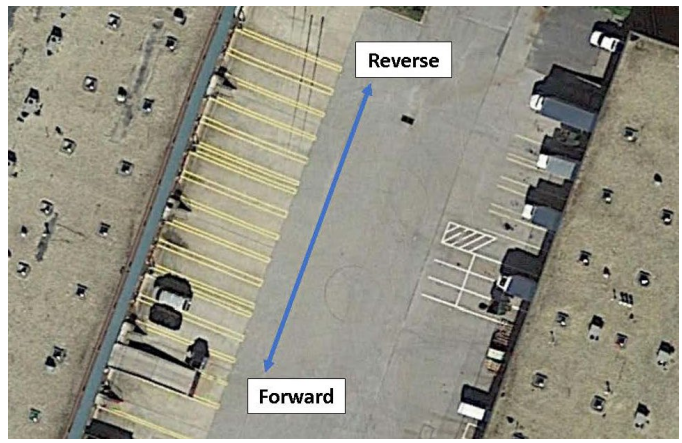

Figure 1. *Aerial view of the location of vehicle testing.*

Figure 2. *Testing location 3D point cloud.*

Figure 3. *Instrumented test vehicle.*

Nine vehicles equipped with conventional automatic transmissions were tested. Specifications for the tested vehicles are shown in Table 1. Full vehicle specifications can be found in Appendix A. Vehicle types included sedans, SUVs, and vans. Vehicle weight was determined from Expert AutoStats. Transmission ratio data were collected from popular automotive journal publications and tire specifications were obtained from manufacturer literature. Prior to each test, the vehicle's engine was allowed to reach operating temperature, which was monitored via the scan tool. Engine-powered accessories, such as air conditioning, were off for testing purposes. Environmental conditions were clear and dry throughout testing.

Table 1. *Tested vehicle specifications.*

Year	Make	Model	EPA Class
2008	Ford	E-250	Cargo Van
2012	Honda	Odyssey	Minivan
2019	Toyota	Sienna	Minivan
2005	Mercury	Mariner	Small SUV
2019	Toyota	RAV4	Small SUV
2013	Toyota	4Runner	Standard SUV
2017	Toyota	Highlander	Standard SUV
2014	Lexus	IS250	Compact sedan
2015	Hyundai	Sonata	Midsize sedan

For forward first gear testing, the vehicle's front axle was aligned with the center of the first double yellow line of the northmost parking space (Figure 1). The brake was released and the vehicle was allowed to roll forward at idle speed for over 200 ft after which the brakes were applied to bring the vehicle to a stop. For reverse runs, the vehicle's front axle was aligned with the appropriate yellow line (Figure 1) and the transmission was shifted into reverse. The vehicle was again allowed to roll backward at idle speed for over 200 ft. A total of three forward runs and three reverse runs were conducted for each vehicle.

Vehicle Testing Results

A total of 54 runs were performed. The VBOX velocity data and IMU acceleration data were filtered with a triple-pass moving average. The VBOX velocity data was integrated and compared to the IMU acceleration data as a data check. Figure 4 and Figure 5 show the filtered velocity data for the Toyota 4Runner plotted against distance for the forward and reverse runs, respectively. Plots for all tested vehicles can be found in Appendix B.

Figure 4 and Figure 5 show a sharp rise in vehicle speed in the first approximate 10-20 ft, then a fluctuation in speed after 20 ft until the vehicle reaches its maximum velocity. The fluctuation in speed is likely due to a fluctuation in engine speed as the engine controls attempt to maintain a set idle speed as the vehicle traverses an irregular road surface. Table 2 shows results from the 54 tests.

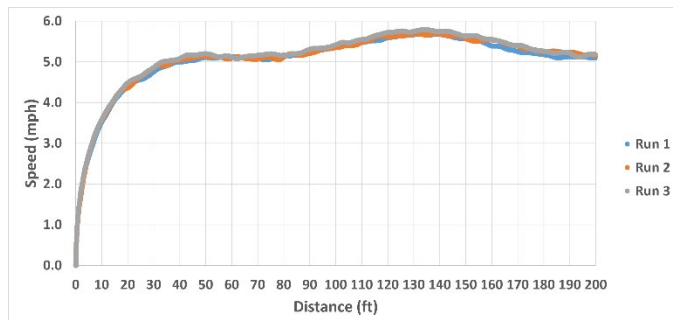

Figure 4. *Testing results for the Toyota 4Runner, forward runs.*

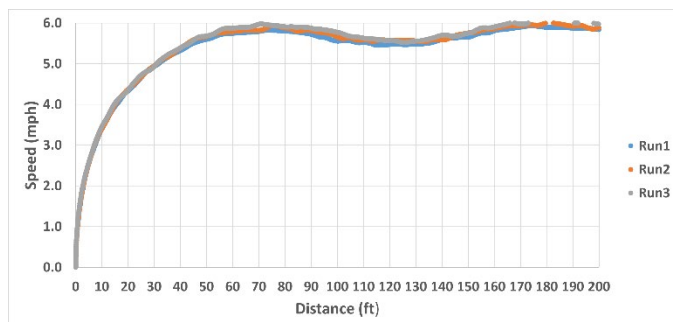

Figure 5. *Testing results for the Toyota 4Runner, reverse runs.*

Table 2. *Vehicle testing results.*

	Vehicle Testing					
Vehicle	Runs	Ave G to 20 ft	Peak G	20 ft Speed	Max Speed	Distance to Max Speed
Ford Econoline	Forward	0.03	0.05	4.0	5.6	140.2
	Reverse	0.02	0.04	3.8	6.4	181.2
Honda Odyssey	Forward	0.03	0.05	3.7	5.0	128.3
	Reverse	0.01	0.03	3.1	5.6	213.8
Toyota Sienna	Forward	0.03	0.07	4.0	4.9	129.5
	Reverse	0.03	0.05	3.8	4.8	187.0
Mercury Mariner	Forward	0.01	0.03	3.2	5.1	129.2
	Reverse	0.01	0.02	2.8	5.7	208.7
Toyota RAV4	Forward	0.01	0.06	2.7	3.0	125.5
	Reverse	0.02	0.05	3.5	4.2	61.4
Toyota 4Runner	Forward	0.02	0.07	4.4	5.7	131.7
	Reverse	0.03	0.06	4.4	6.0	176.8
Toyota Highlander	Forward	0.01	0.04	3.0	3.6	129.5
	Reverse	0.02	0.03	3.0	3.8	61.6
Lexus IS250	Forward	0.01	0.04	2.6	3.3	128.7
	Reverse	0.02	0.04	3.3	4.2	174.9
Hyundai Sonata	Forward	0.03	0.06	4.6	4.9	127.4
	Reverse	0.03	0.04	4.5	5.7	68.4

Results indicate an average acceleration of 0.02 g with a standard deviation of 0.01 g over the first 20 ft of forward testing across all vehicles. Average peak acceleration over

the same distance was 0.05 g with a standard deviation of 0.01 g. Average maximum speed was 4.6 mph with a standard deviation of 1.0 mph. Forward maximum speed across all vehicles ranged from 3.0-5.7 mph and was achieved at distances ranging from 126-140 ft. On average, the speed after 20 ft was approximately 79% of the maximum speed achieved. For the reverse runs, an average acceleration of 0.02 g with a standard deviation of 0.01 g over the first 20 ft was achieved. Average peak acceleration over the same distance was 0.04 g with a standard deviation of 0.01 g. Average maximum speed was 5.2 mph with a standard deviation of 0.9 mph. Reverse maximum speed across all vehicles ranged from 3.8-6.4 mph and was achieved at distances ranging from 62-214 ft. On average, the speed after 20 ft was approximately 70% of the maximum speed achieved.

Acceleration and velocity results from this study for both the forward and reverse testing compare well with previous published studies [1-3]. However, those studies did not include engine speed data. This study recorded engine speed at 1 Hz and is shown in Figure 6 and Figure 7 for the Toyota 4Runner forward and reverse runs, respectively. Engine speed data for all tested vehicles can be found in Appendix C.

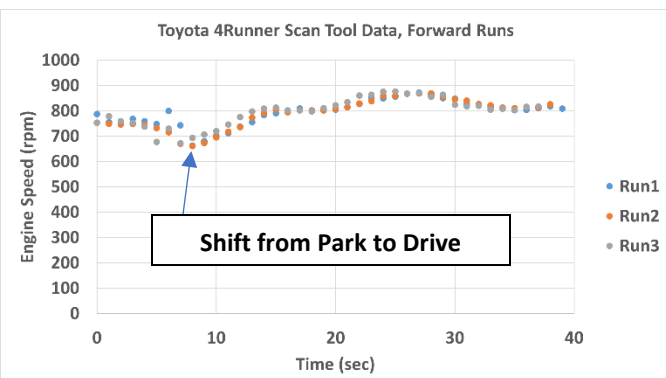

Figure 6. *Toyota 4Runner engine speed data, forward runs.*

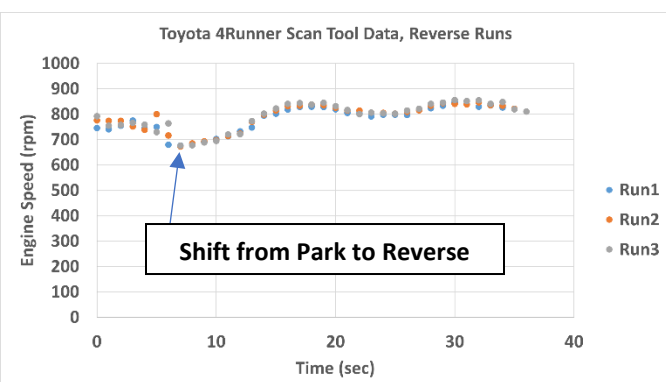

Figure 7. *Toyota 4Runner engine speed data, reverse runs.*

The Toyota 4Runner data show a steady engine speed at approximately 750 rpm while the vehicle was idling in Park. When the vehicle was shifted from Park to Drive or Reverse, there was a drop in engine speed of approximately 100 rpm. This is expected as the engine becomes loaded when the transmission is engaged. The engine speed then rises above the set Park idle speed, steadily increasing to the set Drive or Reverse idle speed of approximately 850 rpm. Again, the rise in idle speed is expected as the increase in engine speed is necessary to keep the engine from stalling under load. Most of the tested vehicles followed this trend, either increasing engine speed to the set Park idle speed once the vehicle was shifted to Drive or Reverse, or to a higher set Drive/Reverse idle speed. Two vehicles, the Mercury Mariner and the Honda Odyssey in their respective reverse runs, actually had engine speed fall below the set Park idle speed once the vehicle was shifted to Reverse and maintain that lower engine speed throughout reverse testing. Most vehicles idled around 700 rpm (rounded to the nearest 100 rpm) while in Park.

The authors attempted to find a correlation between engine idle speed and a known vehicle parameter. Those parameters included vehicle class, vehicle weight, wheelbase, peak engine horsepower, power-to-weight ratio, and the quantity of $T_R \times R_T \times R_A$. No statistical correlation was found among those parameters. Even vehicles from the same manufacturer and vehicle class (Toyota 4Runner and Toyota Highlander) did not share any similar idling characteristics.

Theoretical Comparison

Using the engine speed data collected from the scan tool during testing after the transmission was shifted from Park to Drive or Reverse and while the vehicle was in motion, a maximum forward or reverse speed was calculated using Equation 1. The average engine speed for each vehicle was rounded to the nearest 100 rpm for the calculation. This theoretical maximum speed was then compared to the average maximum VBOX filtered speeds obtained from the forward and reverse runs for each vehicle.

Results are shown in Table 3 for the forward runs and Table 4 for the reverse runs. Table 3 generally shows good agreement with Equation 1 except for the Hyundai Sonata. Excluding the Hyundai Sonata, which produced approximately 20% error, Equation 1 estimated the

observed maximum speed generally within ±5%. The reverse maximum speed prediction (Table 4) produced greater error compared to the forward runs. Error ranged from approximately 1%-29%, however, unlike the forward case, Equation 1 for the reverse runs always overpredicted the maximum speed compared to the average maximum VBOX speeds.

Table 3. *Theoretical maximum speed comparison, forward runs.*

Vehicle	Observed RPM	Equation 1 Speed	Max VBOX Speed	% Error
Ford E-250	700	5.8	5.6	4.1%
Honda Odyssey	700	5.0	5.0	0.8%
Toyota Sienna	1000	5.0	4.9	3.0%
Mercury Mariner	700	5.3	5.1	4.8%
Toyota RAV4	600	3.0	3.0	-1.5%
Toyota 4Runner	800	5.5	5.7	-2.7%
Toyota Highlander	700	3.6	3.6	0.5%
Lexus IS250	700	3.5	3.3	5.4%
Hyundai Sonata	900	5.9	4.9	19.6%

Table 4. *Theoretical maximum speed comparison, reverse runs.*

Vehicle	Observed RPM	Equation 1 Speed	Max VBOX Speed	% Error
Ford E-250	700	7.1	6.4	11.5%
Honda Odyssey	700	7.2	5.6	28.7%
Toyota Sienna	800	5.3	4.8	10.1%
Mercury Mariner	700	6.7	5.7	17.4%
Toyota RAV4	700	4.5	4.2	7.5%
Toyota 4Runner	800	6.1	6.0	1.1%
Toyota Highlander	700	4.7	3.8	24.5%
Lexus IS250	800	4.4	4.2	5.1%
Hyundai Sonata	800	6.5	5.7	13.8%

HVE Simulation Procedure

In HVE SIMON, vehicle acceleration is controlled with either the percent wide-open throttle (WOT) table or tractive effort table. The percent WOT table drives both the WOT curve and closed throttle (CT) curve in the drivetrain dialog (Figure 8 and Figure 9). When a value is entered in the percent WOT table, the user is defining the amount of horsepower the vehicle is producing at a given engine speed as a percentage between the WOT curve and the CT curve. When a value of 0% is entered in the table, the HVE will return a horsepower value on the CT curve; likewise, when 100% is entered, the model will return a horsepower value on the WOT curve. If a value between 0-100% is entered, say 20%, a horsepower value 20% between the CT curve value and WOT curve value will be used by the model for a given engine speed. Thus, when 0% is entered in the percent WOT table, the model is on the CT curve (Figure 9) at idle speed with the engine producing negative horsepower and the vehicle does not move. Therefore, the percent WOT table is neither modeling the amount the accelerator pedal is depressed nor the amount the butterfly valve is open, since the butterfly valve must remain open some percentage at idle to keep the engine running. To account for the real-world phenomenon of engine idle vehicle creep, adjustments to the CT horsepower versus engine speed curve are therefore needed to account for the small amount of torque passed to the transmission at idle.

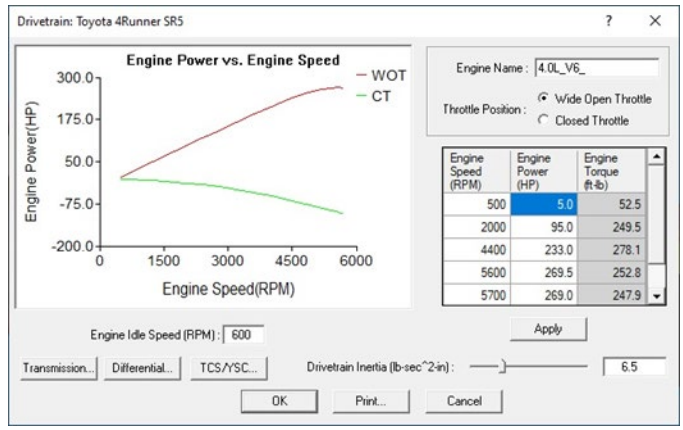

Figure 8. *2010-2020 Toyota 4Runner WOT and CT curves, WOT values.*

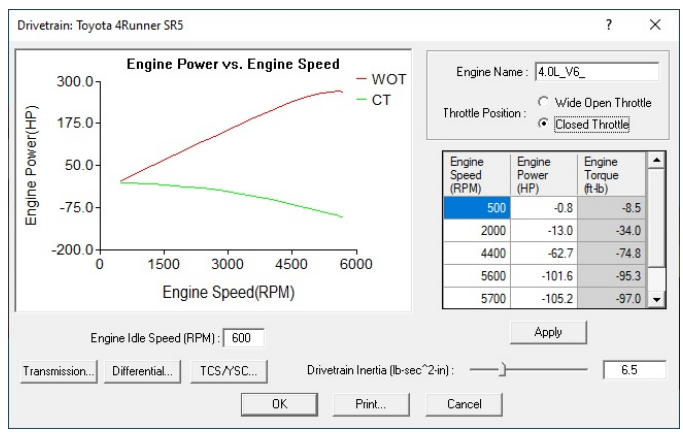

Figure 9. *2010-2020 Toyota 4Runner WOT and CT curves, CT values.*

The Summer 2013 EDC Technical Newsletter [4] outlines the methodology HVE uses to calculate engine torque. The flow chart within the newsletter indicates wheel speed is first calculated, then road engine speed and engine speed, so that engine torque can ultimately be determined (see Figure 10). Engine speed is equal to either the maximum defined engine idle speed, or in this case, the calculated road engine speed. Figure 10 then indicates the next step in the calculation is to determine the WOT/CT engine torque. Since 0% throttle was entered in the percent WOT table, the calculation will be performed using the CT curve only. A torque converter is

used so clutch slip will be calculated and then finally, engine torque is calculated.

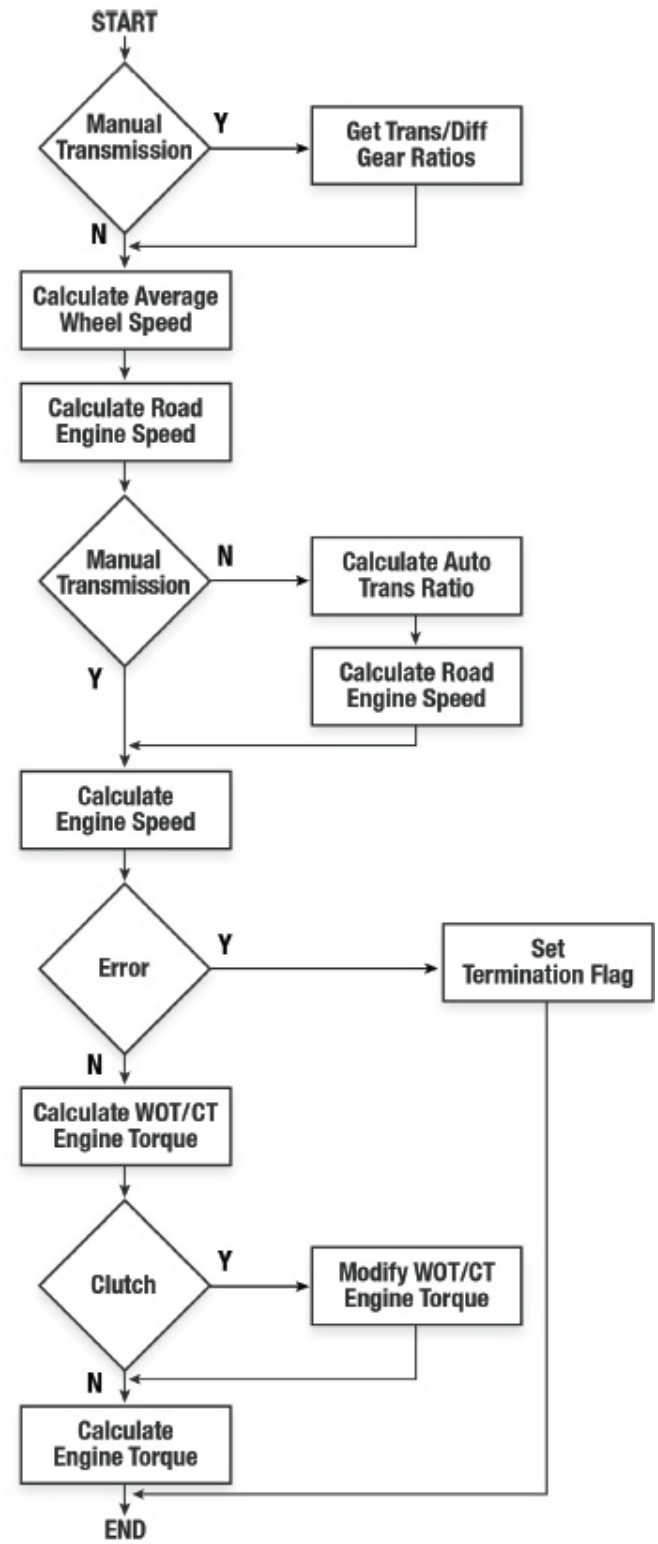

Figure 10. *Drivetrain calculation flow chart. Courtesy of EDC.*

To generate the CT horsepower versus engine speed curve used in the drivetrain dialog, wheel speed and road engine speed were calculated from the VBOX filtered vehicle speed, transmission ratio, differential ratio, and tire revolutions per mile at each time step. To calculate engine horsepower, engine torque was first calculated from the IMU filtered acceleration data, vehicle weight, transmission ratio, differential ratio, and rolling radius of the tire. Engine horsepower was then calculated from the engine torque, for a given road engine speed from the following equation:

$$HP = \frac{Torque \times RPM}{5252} \qquad (2)$$

where HP is the engine horsepower and RPM is the road engine speed. The process was repeated for each forward and reverse run. The calculated horsepower for the forward runs were then averaged together as well as the reverse runs for each vehicle in increments of 100 rpm, starting at 100 rpm. The engine idle speed was also set to 100 rpm for all vehicles. In this fashion, a CT horsepower versus engine speed curve was generated.

An HVE environment was created using 3D Studio Max and the FARO 3D scan data collected during the vehicle testing phase of the study. All of the tested vehicles were available in the HVE vehicle database. HVE vehicle model transmission ratios, final drive ratios, and tire sizes were checked and adjusted as necessary to match tested vehicle specifications. Vehicle models were placed in the HVE environment at the defined forward (Figure 11) or reverse travel starting locations. No throttle or braking inputs were defined for driver controls (Use Clutch/Torque Converter was checked) and the vehicle's initial velocity was set to 0 mph. Maximum simulation time was set to allow the vehicle to travel at least 200 ft. In some instances, the vehicle did not reach 200 ft in the maximum HVE-allowed simulation time of 40 sec.

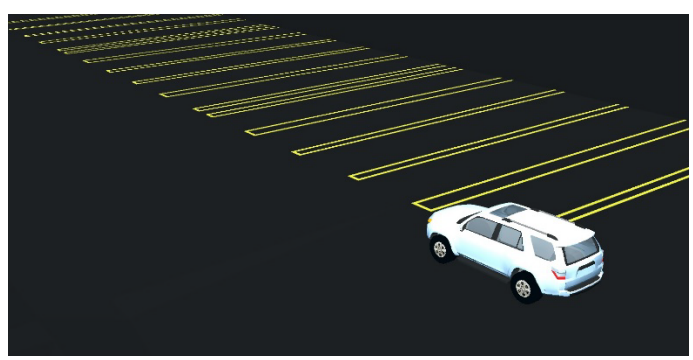

Figure 11. *HVE environment using the 2010-2020 Toyota 4Runner positioned for the forward runs.*

HVE Simulation Results

After initial simulations, the generated CT engine speed and horsepower values did not result in a good match to the observed vehicle accelerations, speed at 20 ft of travel, and maximum speed in the forward and reverse runs. The authors performed sensitivity analysis around several HVE parameters that would affect the wheel speed and torque calculations within the model. These included drivetrain inertia, tire weight, tire spin inertia, and tire rolling resistance constant. These parameters did affect the vehicle speed trace, however, not to the degree necessary to obtain a good match to the VBOX data. Further, the authors did not have a reasonable justification for changes to these parameters from the default values. In addition, the values for these parameters would need adjusting in opposite directions for the forward and reverse runs (i.e., values for drivetrain inertia would need to be raised in the forward runs and lowered in the reverse runs). Therefore, the authors introduced a torque multiplier to Equation 2 as:

$$HP = \frac{C_{fwd} \times Torque \times RPM}{5252} \qquad (3)$$

$$HP = \frac{C_{rev} \times Torque \times RPM}{5252} \qquad (4)$$

where C_{fwd} is a constant needed to increase the torque to an appropriate value for increased agreement to the VBOX data in the forward runs and C_{rev} is a constant needed to increase the torque to an appropriate value for increased agreement to the VBOX data in the reverse runs. The forward and reverse constants were considered optimized when the speed at 20 ft and maximum speed were near agreement with the VBOX data.

Optimized constants for each vehicle can be found in Appendix A. Constants ranged from 1.0 to 2.0 for forward runs and 1.2 to 2.2 for reverse runs, with an average of 1.3 with a standard deviation of 0.3 for forward runs and an average of 1.6 with a standard deviation of 0.3 for reverse runs. The authors attempted to find a correlation between the torque multiplier constant and a known vehicle parameter. Those parameters included vehicle class, vehicle weight, wheelbase, peak engine horsepower, power-to-weight ratio, and the quantity of $T_R \times R_T \times R_A$. No statistical correlation was found among those parameters.

The modified CT horsepower values are shown in Appendix A. Engine speed ranged from 100 rpm to 1,000 rpm in 100 rpm increments for the forward runs and 100 rpm to 800 rpm for the reverse runs. Horsepower values for the forward runs ranged from 0.0 hp to 2.1 hp for a given 100 rpm increment. Average engine horsepower was 0.7 hp with a standard deviation of 0.2. Reverse runs ranged from 0.0 hp to 1.8 hp for a given 100 rpm increment. Average engine horsepower was 0.7 hp with a standard deviation of 0.1. No statistical correlation was found between vehicle class and CT horsepower for a given 100 rpm increment for either forward or reverse. However, Table 5 shows average horsepower levels for all tested vehicles for a given engine speed were comparable in both forward in reverse runs.

Table 5. *Closed throttle average horsepower comparison for a given engine speed, forward and reverse runs.*

CT RPM	Forward Average	Reverse Average
100	0.4	0.5
200	0.8	0.8
300	1.0	1.0
400	1.0	1.1
500	1.0	0.9
600	0.8	0.6
700	0.5	0.3
800	0.4	0.2
900	0.4	
1000	0.2	

Plots for the HVE results overlayed on the VBOX data for the Toyota 4Runner are shown in Figure 12 and Figure 13 for the forward and reverse runs, respectively. Plots for all tested vehicles can be found in Appendix B. The figures show good agreement with the VBOX data over the first 20 ft of travel, which is the area of most interest to the accident investigator. The simulations follow the rise in speed over the first 20 ft then follows the speed fluctuations after that distance which was observed during vehicle testing. Although the simulations generally follow the speed trace after that distance, HVE begins to underpredict the speed by a small margin for the remainder of the run.

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Table A2 shows the difference between the VBOX speed at 20 ft and the HVE simulations. Average difference was 0.06 mph and 0.03 mph for the forward and reverse runs, respectively. For the maximum speed, the average difference was -0.22 mph and -0.46 mph for the forward and reverse runs, respectively. Since the torque multiplier constant was optimized around the 20 ft speed and maximum speed values, there was a wider range of agreement between the VBOX data and HVE simulations on the average and peak accelerations. The average difference on average accelerations was 0.002 g for the forward direction, and 0.002 g for the reverse direction. Peak gear average difference was -0.002 g and 0.002 g for the forward and reverse runs, respectively.

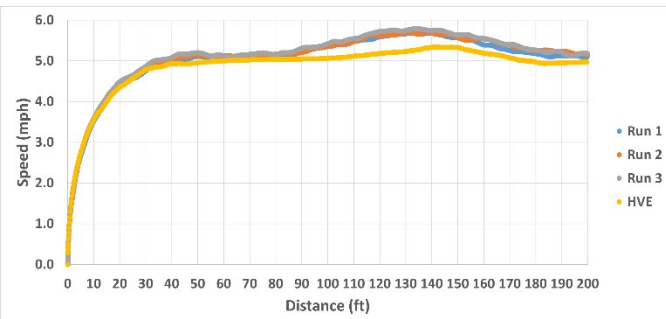


Figure 12. *HVE simulation results overlayed on the VBOX data for the Toyota 4Runner, forward runs.*

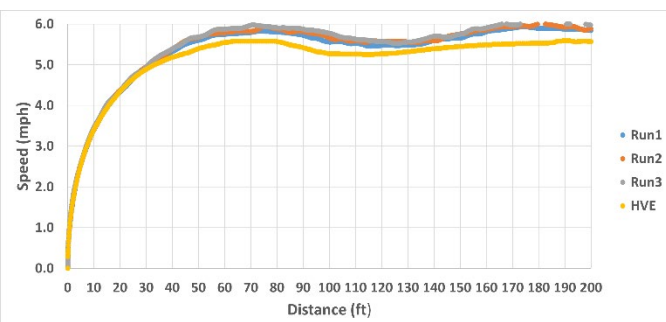


Figure 13. *HVE simulation results overlayed on the VBOX data for the Toyota 4Runner, reverse runs.*

Summary

This paper describes a methodology for using HVE to simulate engine idle creep in vehicles equipped with conventional automatic transmissions in first and reverse gear from real-world testing data. The method entails calculating a road engine speed from observed vehicle speed, calculating the associated engine torque, and converting to horsepower. This methodology emulates the flow chart for how engine torque is calculated in the HVE drivetrain model. In this manner, a CT curve can be generated for use in the drivetrain dialog. Simulation results indicate this method provides acceptable agreement for the 20 ft speed and maximum speed.

No statistical correlation could be determined for relating engine idle speed, torque multiplier constant, or CT horsepower to a known vehicle parameter. Vehicles from the same manufacturer and vehicle class also did not provide any correlation for those values. This could be a result of the small sample size (one cargo van, two mini-vans, four SUVs, and two sedans). Results from previous studies could be incorporated with this paper's results for a larger sample size to provide further insight.

References

1. Rast, P., Stearns, R., Allison, M., Gloekler, T., & Beals, D., "Acceleration Factors and Maximum Speeds Under Conditions of Idle Acceleration," Accident Investigation Quarterly, Issue 23, Summer 2000.
2. Reust, T.J., "Engine Idle Acceleration," ARC-CSI 2008.
3. Randles, B., Voss, D., Ikram, I., Furbish, C., Welcher, J., & Szabo, T., "Acceleration Testing and Modeling of Vehicle Kinematics Under Idle Conditions," SAE paper #201-01-0484, 2014.
4. Engineering Dynamics Corporation, "Technical Newsletter," Summer 2013.

APPENDIX A

Table A1. *Tested vehicle specifications.*

Year	Make	Model	EPA Class	Wheelbase	HP	Curb Weight	1st Gear	Reverse Gear	Final Drive	Tire Size	Revs/Mile
2008	Ford	E-250	Cargo Van	138	255	5383	2.84	2.32	3.73	LT245/75R16	680
2012	Honda	Odyssey	Minivan	118	248	4477	2.69	1.88	4.31	235/65R17	719
2019	Toyota	Sienna	Minivan	119	295	4590	5.52	4.22	3.00	235/60R17	718
2005	Mercury	Mariner	Small SUV	103	200	3304	2.89	2.31	3.77	235/70R16	721
2019	Toyota	RAV4	Small SUV	106	203	3555	5.25	4.01	3.18	225/65R17	729
2013	Toyota	4Runner	Standard SUV	110	270	4740	3.52	3.22	3.73	LT265/70R17	659
2017	Toyota	Highlander	Standard SUV	110	295	4551	5.52	4.22	3.00	245/60R18	701
2014	Lexus	IS250	Compact Sedan	110	204	3649	3.52	3.17	4.10	225/45R17	837
2015	Hyundai	Sonata	Midsize Sedan	110	185	3378	4.21	3.38	2.88	215/55R17	760

Table A2. *Tested vehicle results compared to HVE simulation results.*

	Vehicle Testing						HVE Simulations							Difference					
Vehicle	Runs	Ave G to 20 ft	Peak G	20 ft Speed	Max Speed	Distance to Max Speed	Runs	Ave G to 20 ft	Peak G	20 ft Speed	Max Speed	Distance to Max Speed	Constant	Runs	Ave G to 20 ft	Peak G	20 ft Speed	Max Speed	Distance to Max Speed
Ford Econoline	Forward	0.03	0.05	4.0	5.6	140.2	Forward	0.03	0.05	4.1	5.4	150.9	1.0	Forward	-0.001	-0.003	0.06	-0.26	10.7
	Reverse	0.02	0.04	3.8	6.4	181.2	Reverse	0.02	0.04	3.8	5.7	187.5	1.4	Reverse	0.000	0.004	0.03	-0.64	6.3
Honda Odyssey	Forward	0.03	0.05	3.7	5.0	128.3	Forward	0.03	0.05	3.8	4.7	148.49	1.0	Forward	-0.001	-0.003	0.06	-0.27	20.2
	Reverse	0.01	0.03	3.1	5.6	213.8	Reverse	0.02	0.03	3.2	4.8	189.9	1.8	Reverse	0.003	-0.002	0.09	-0.80	-23.8
Toyota Sienna	Forward	0.03	0.07	4.0	4.9	129.5	Forward	0.03	0.06	4.2	4.5	141.3	1.2	Forward	-0.002	-0.013	0.15	-0.41	11.8
	Reverse	0.03	0.05	3.8	4.8	187.0	Reverse	0.03	0.05	3.8	4.5	62.6	1.4	Reverse	-0.004	0.003	0.02	-0.38	-124.4
Mercury Mariner	Forward	0.01	0.03	3.2	5.1	129.2	Forward	0.02	0.03	3.2	4.9	147.7	1.4	Forward	0.004	0.004	-0.01	-0.21	18.5
	Reverse	0.01	0.02	2.8	5.7	208.7	Reverse	0.01	0.02	2.7	5.43	199.7	2.0	Reverse	0.001	-0.001	-0.09	-0.27	-9.1
Toyota RAV4	Forward	0.01	0.06	2.7	3.0	125.5	Forward	0.01	0.04	2.8	2.9	141.1	2.0	Forward	-0.002	-0.016	0.10	-0.12	15.7
	Reverse	0.02	0.05	3.5	4.2	61.4	Reverse	0.02	0.05	3.6	3.9	61.1	2.2	Reverse	0.002	0.000	0.08	-0.33	-0.3
Toyota 4Runner	Forward	0.02	0.07	4.4	5.7	131.7	Forward	0.03	0.06	4.4	5.3	140.4	1.0	Forward	0.010	-0.009	-0.03	-0.38	8.7
	Reverse	0.03	0.06	4.4	6.0	176.8	Reverse	0.03	0.05	4.3	5.6	188.4	1.2	Reverse	0.000	-0.008	-0.01	-0.42	11.6
Toyota Highlander	Forward	0.01	0.04	3.0	3.6	129.5	Forward	0.02	0.04	3.0	3.3	141.3	1.2	Forward	0.002	-0.003	0.02	-0.30	11.7
	Reverse	0.02	0.03	3.0	3.8	61.6	Reverse	0.02	0.04	3.0	3.3	60.4	1.6	Reverse	0.002	0.009	0.01	-0.51	-1.3
Lexus IS250	Forward	0.01	0.04	2.6	3.3	128.7	Forward	0.01	0.04	2.7	3.4	146.3	1.2	Forward	0.002	0.002	0.15	0.05	17.6
	Reverse	0.02	0.04	3.3	4.2	174.9	Reverse	0.02	0.04	3.4	4.0	62.0	1.4	Reverse	0.003	-0.001	0.03	-0.26	-112.9
Hyundai Sonata	Forward	0.03	0.06	4.6	4.9	127.4	Forward	0.04	0.08	4.6	4.8	140.6	1.6	Forward	0.009	0.024	0.03	-0.09	13.1
	Reverse	0.03	0.04	4.5	5.7	68.4	Reverse	0.04	0.05	4.6	5.2	60.7	1.8	Reverse	0.012	0.015	0.12	-0.51	-7.7

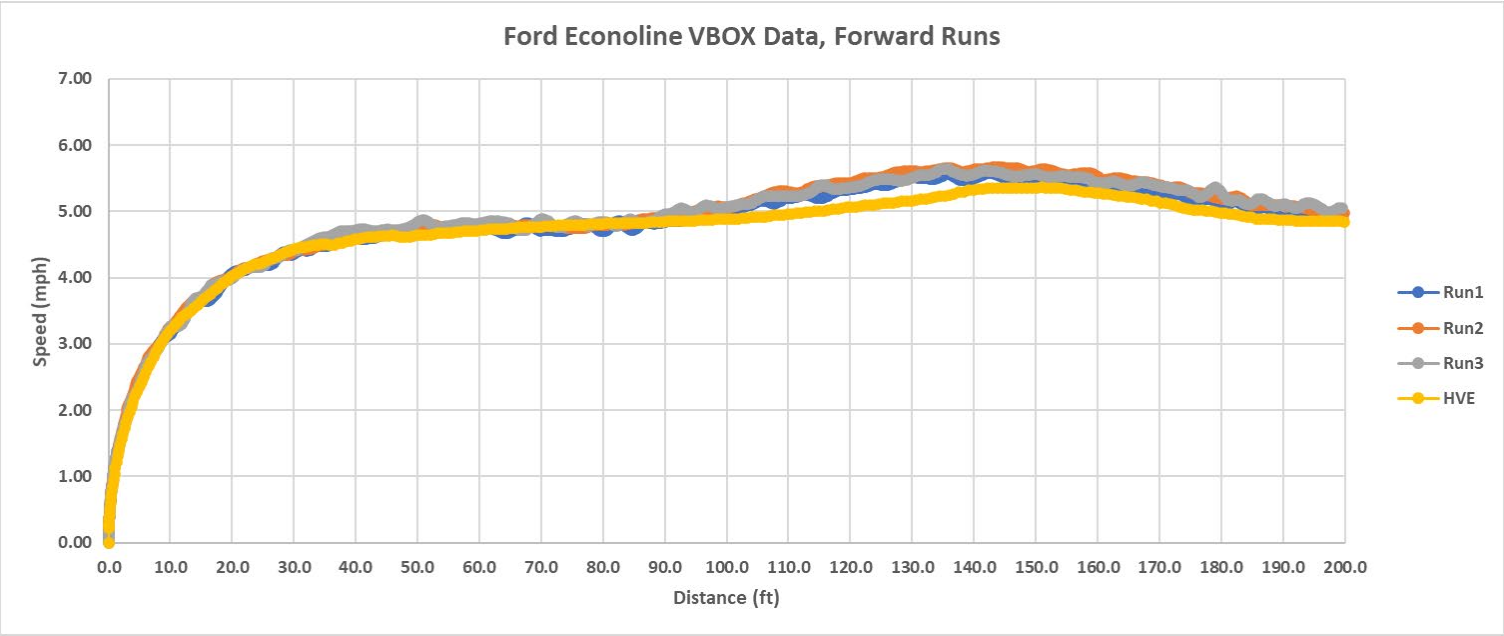
Table A3. *Closed throttle horsepower values, forward runs.*

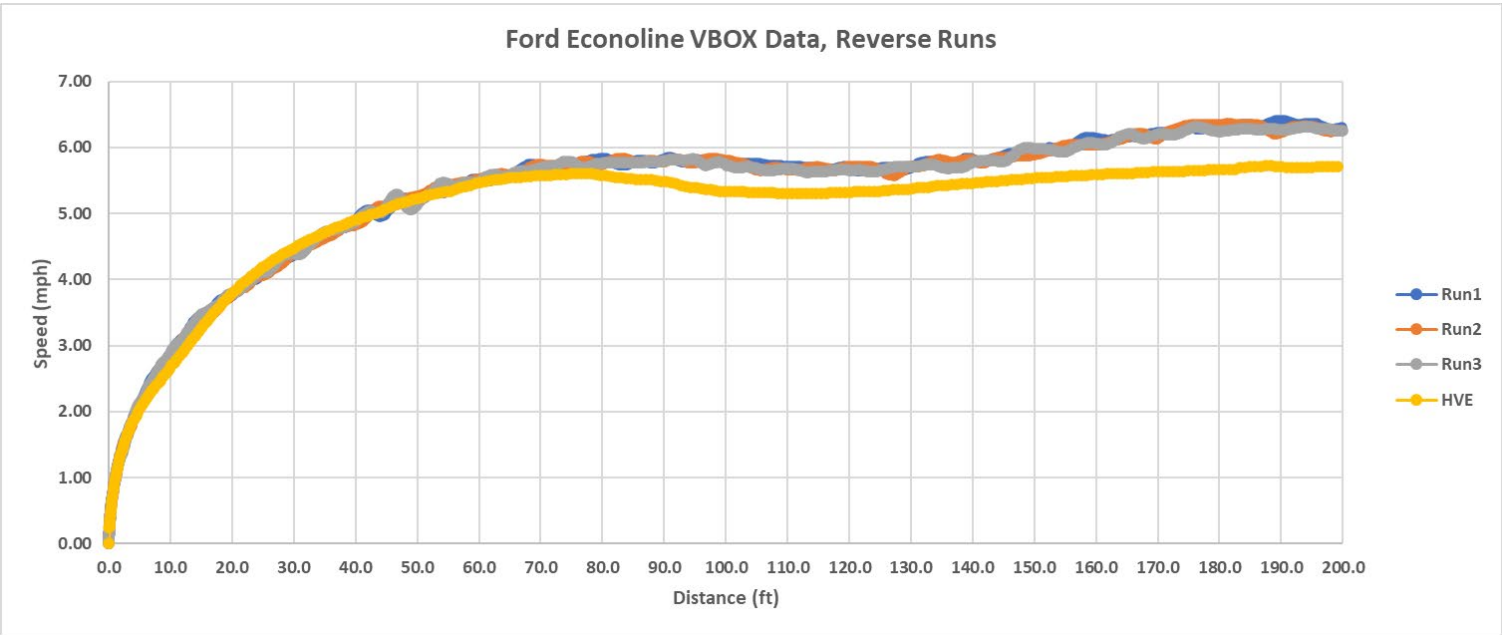
CT RPM	Ford E-250	Honda Odyssey	Toyota Sienna	Mercury Mariner	Toyota RAV4	Toyota 4Runner	Toyota Highlander	Lexus IS250	Hyundai Sonata
100	0.6	0.5	0.6	0.2	0.5	0.6	0.3	0.2	0.5
200	1.1	0.8	1.1	0.4	0.8	1.2	0.6	0.4	1.1
300	1.4	0.9	1.4	0.4	0.6	1.5	0.8	0.3	1.5
400	1.3	0.9	1.5	0.6	0.6	1.6	0.6	0.3	1.9
500	1.0	0.9	1.5	0.8	0.4	1.5	0.5	0.3	2.1
600	0.3	0.7	1.4	0.4	0.0	1.4	0.3	0.3	2.1
700	0.0	0.2	1.3	0.3		1.2	0.0	0.1	0.9
800			1.2			0.1			0.0
900			0.4						
1000			0.2						

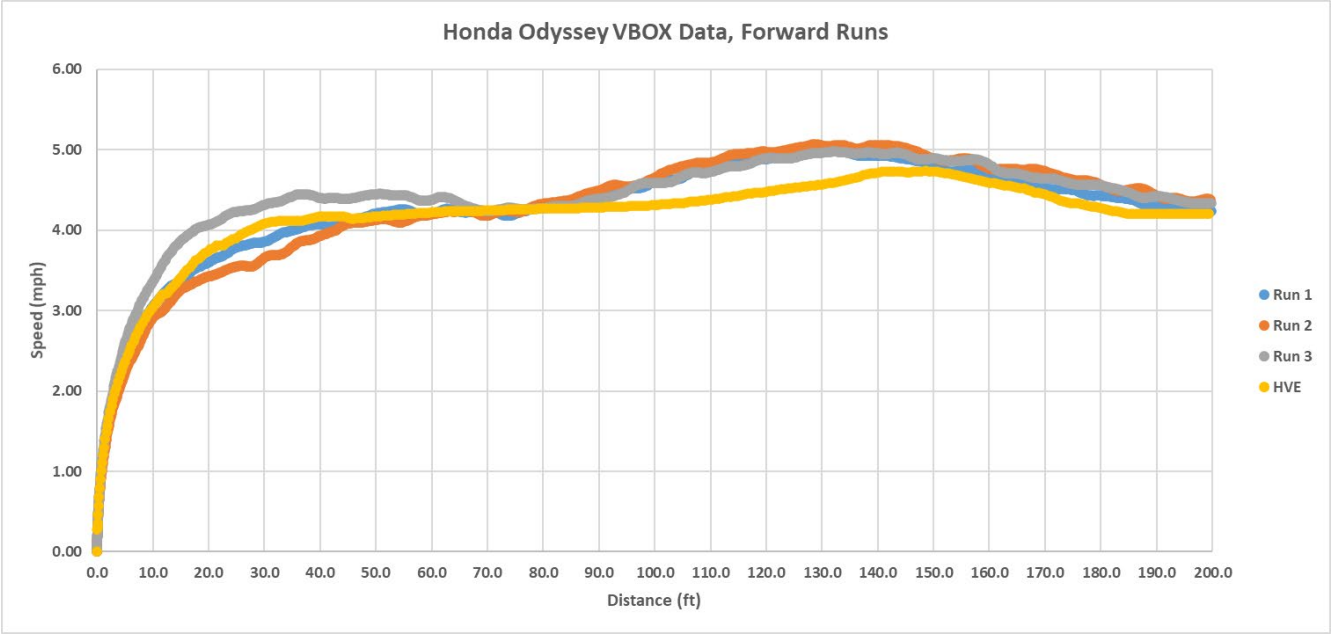
Table A4. *Closed throttle horsepower values, reverse runs.*

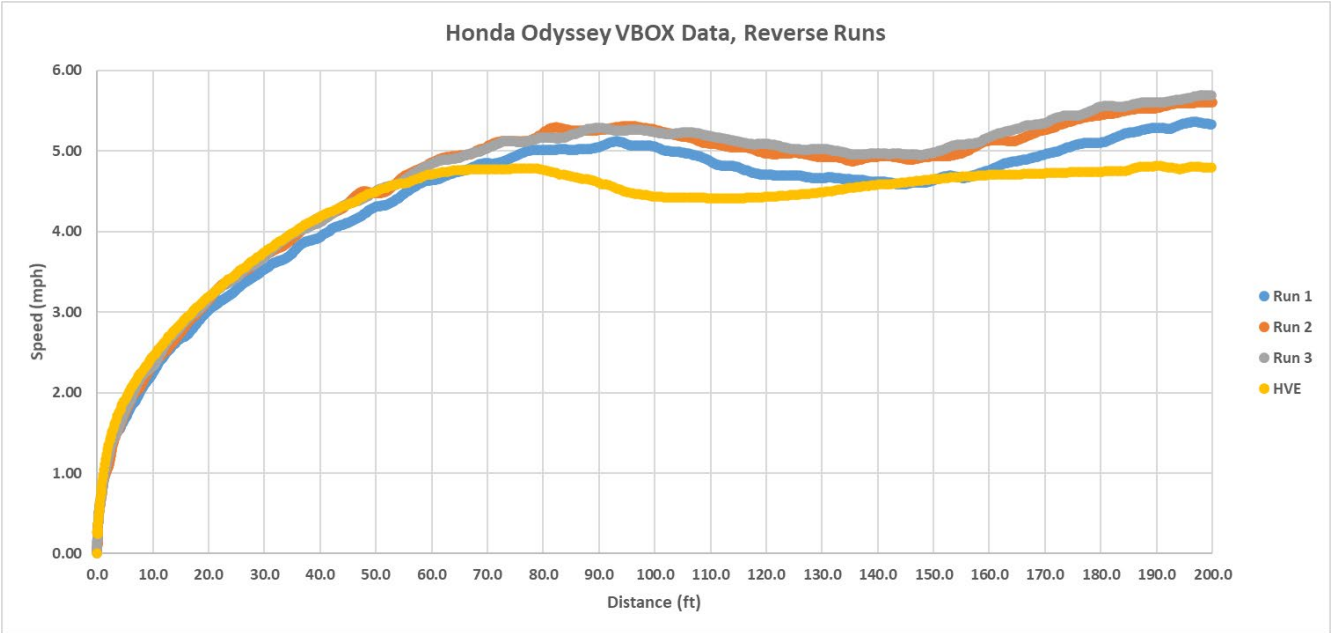
CT RPM	Ford E-250	Honda Odyssey	Toyota Sienna	Mercury Mariner	Toyota RAV4	Toyota 4Runner	Toyota Highlander	Lexus IS250	Hyundai Sonata
100	0.7	0.5	0.6	0.2	0.4	0.6	0.4	0.3	0.5
200	0.9	0.6	1.0	0.3	0.7	1.1	0.8	0.6	0.9
300	1.8	0.8	1.1	0.7	0.8	1.5	0.7	0.6	1.2
400	1.5	1.0	1.2	0.5	1.0	1.8	0.7	0.6	1.6
500	0.7	0.3	1.3	0.6	0.8	1.7	0.2	0.8	1.5
600	0.2	0.1	0.9	0.6	0.2	1.7	0.1	0.5	1.1
700	0.5		0.4		0.0	1.0		0.2	0.0
800			0.3			0.1		0.3	

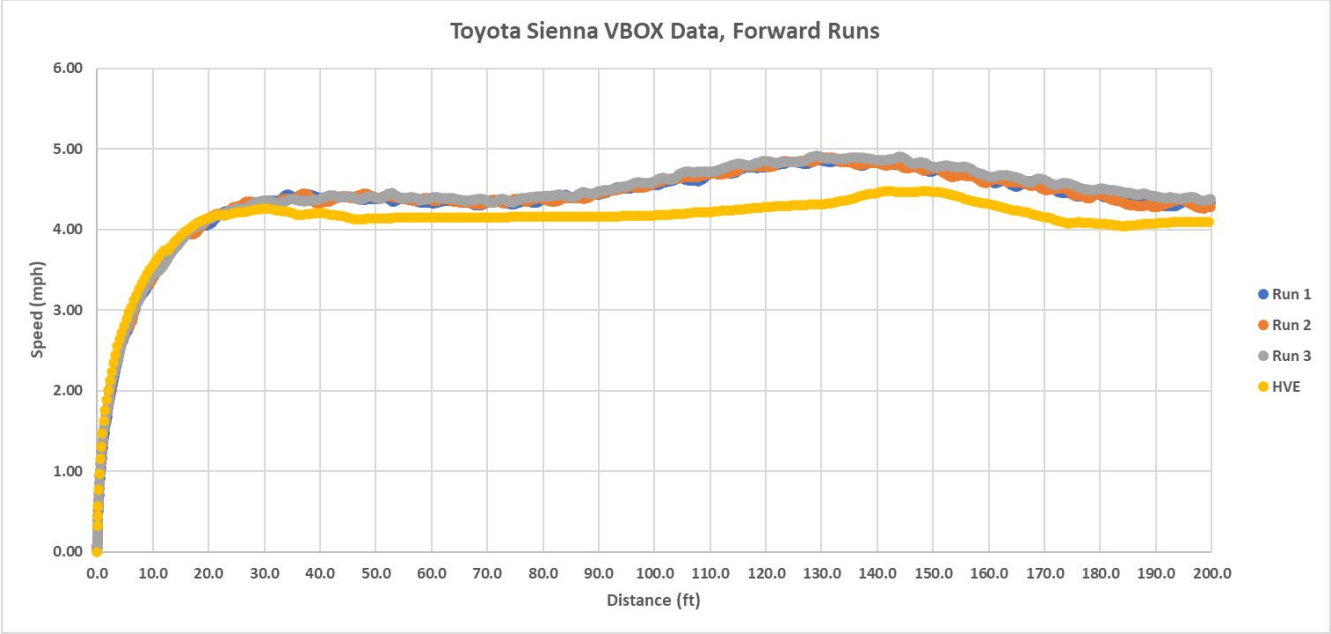
APPENDIX B

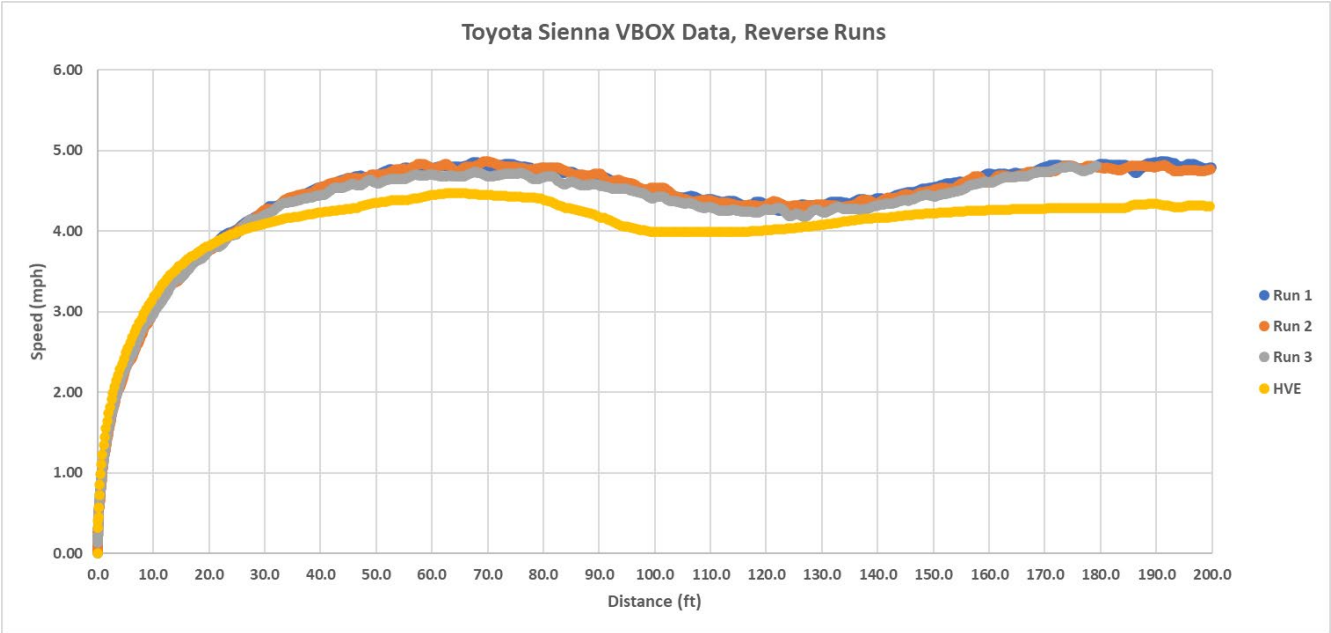

Ford Econoline VBOX Data, Forward Runs
Speed (mph)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run1
Run2
Run3
HVE

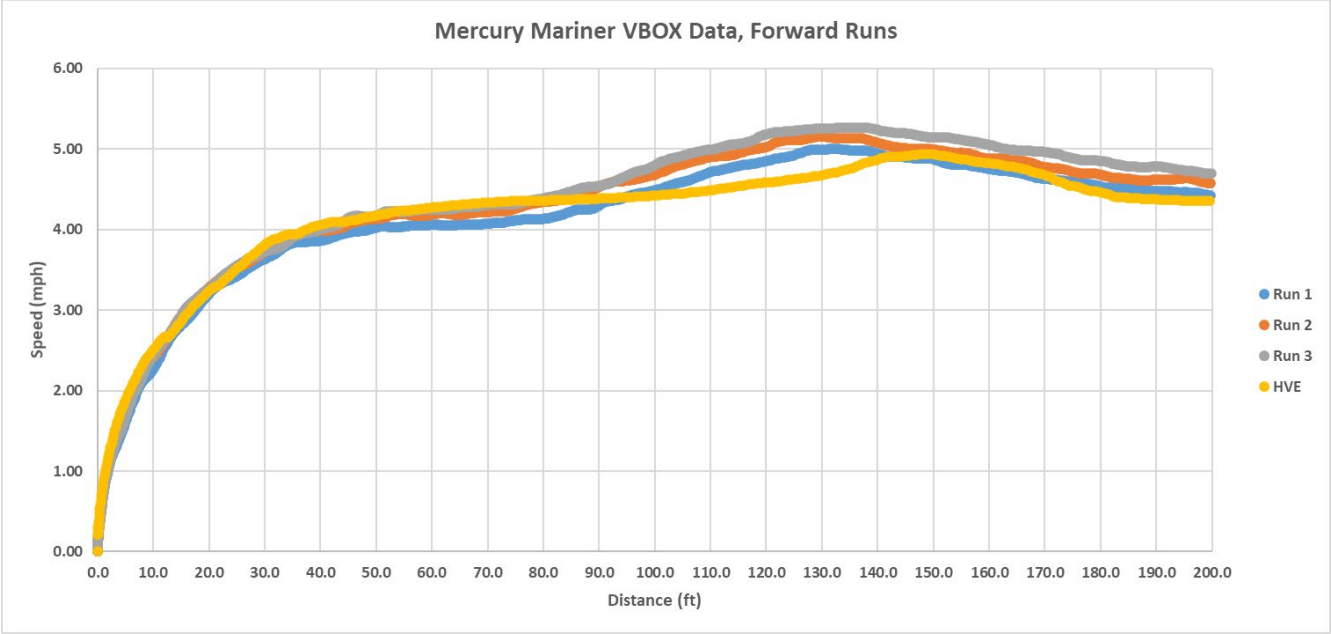

Ford Econoline VBOX Data, Reverse Runs
Speed (mph)
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run1
Run2
Run3
HVE

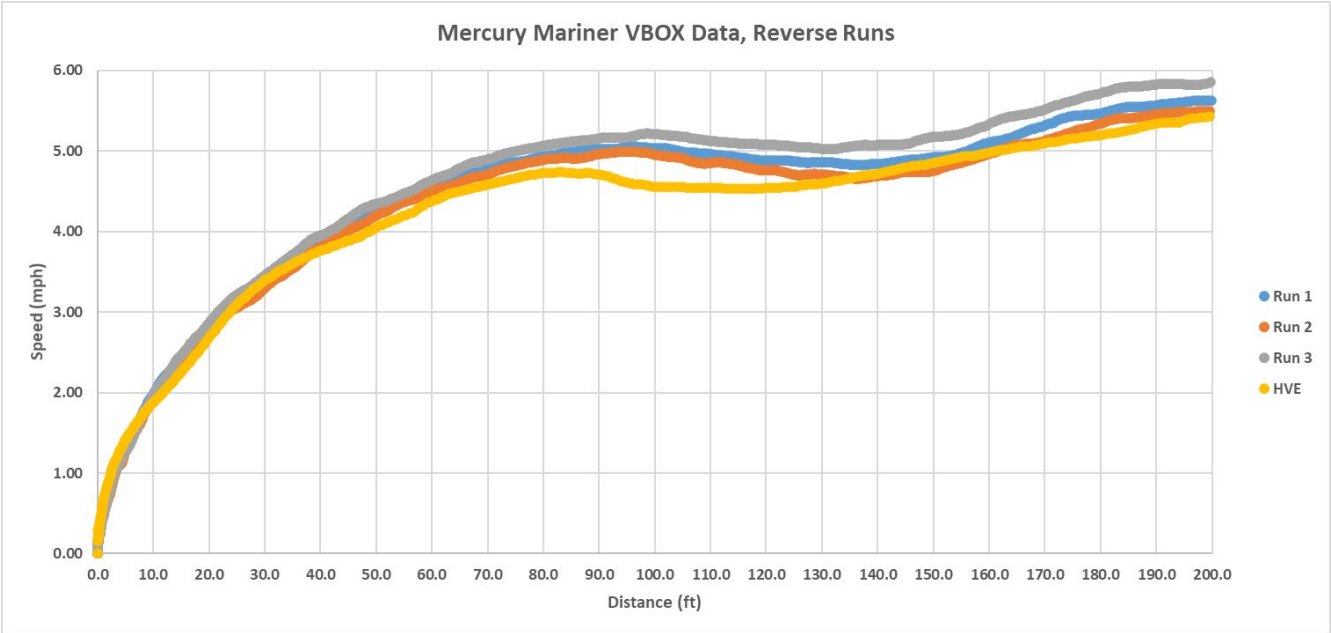

Honda Odyssey VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

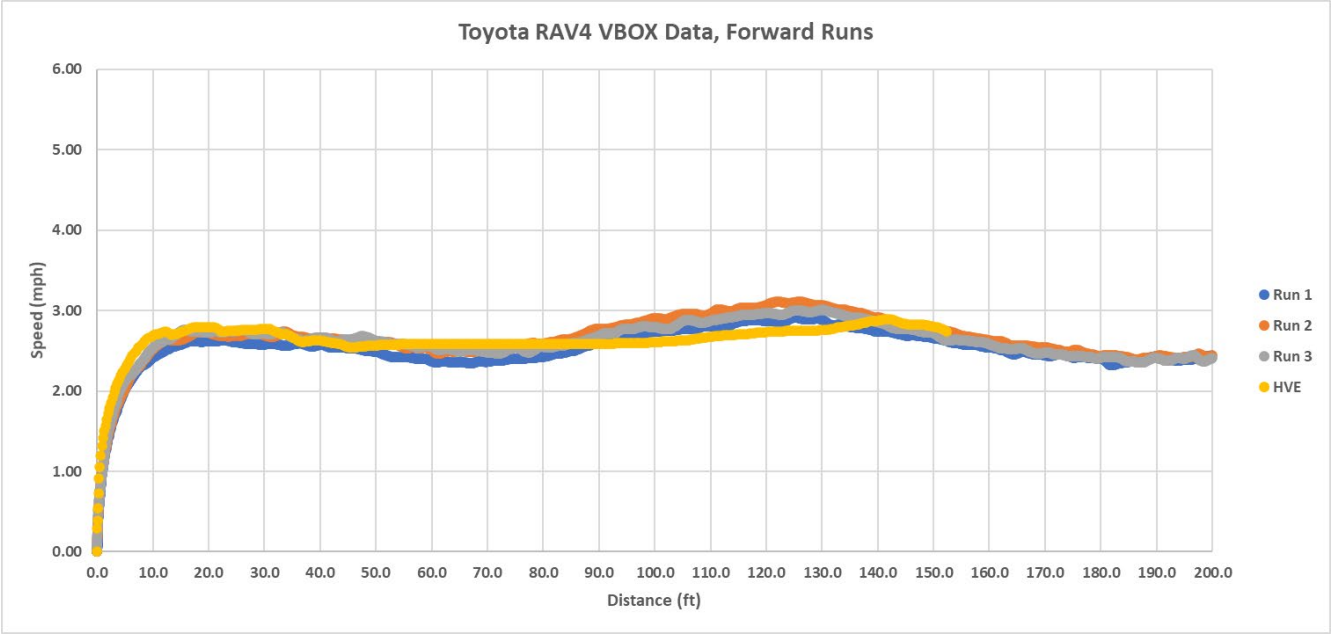

Honda Odyssey VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

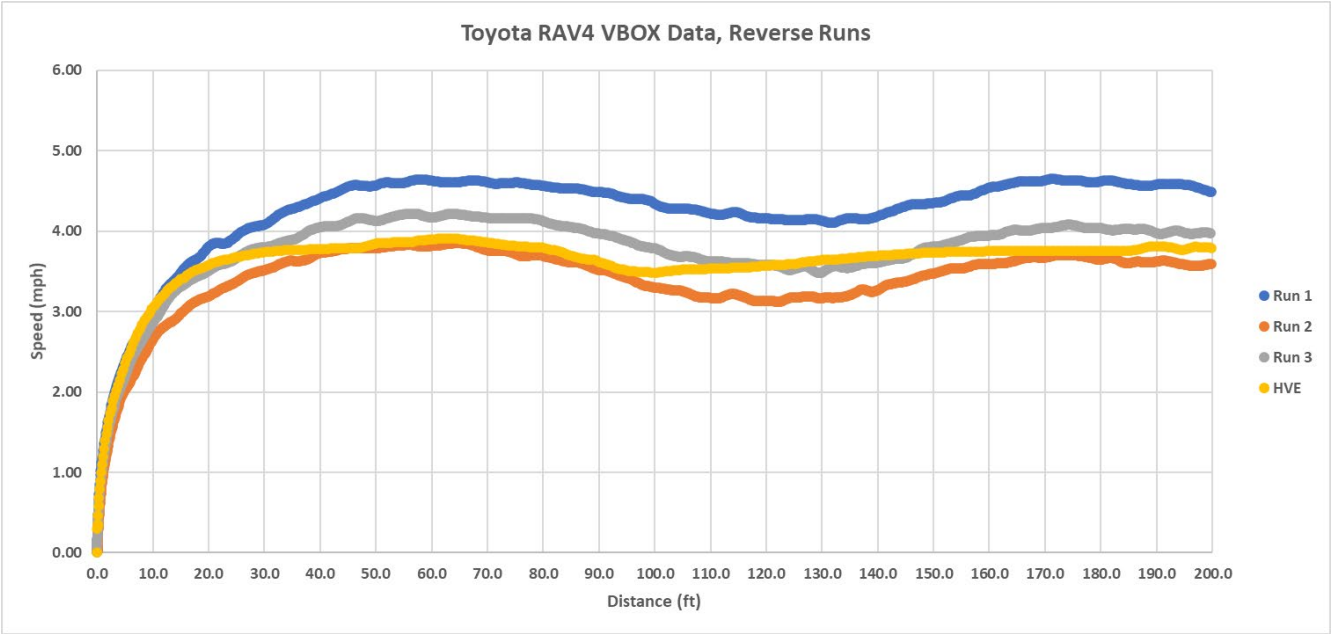

Toyota Sienna VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

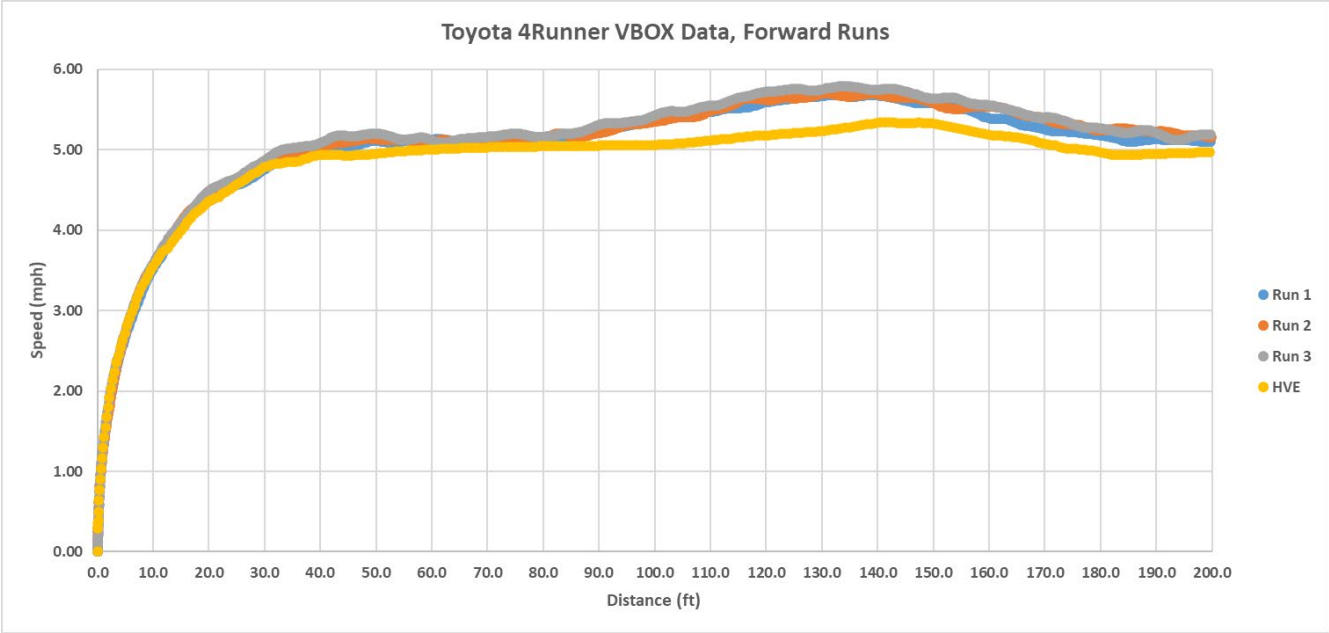

Toyota Sienna VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

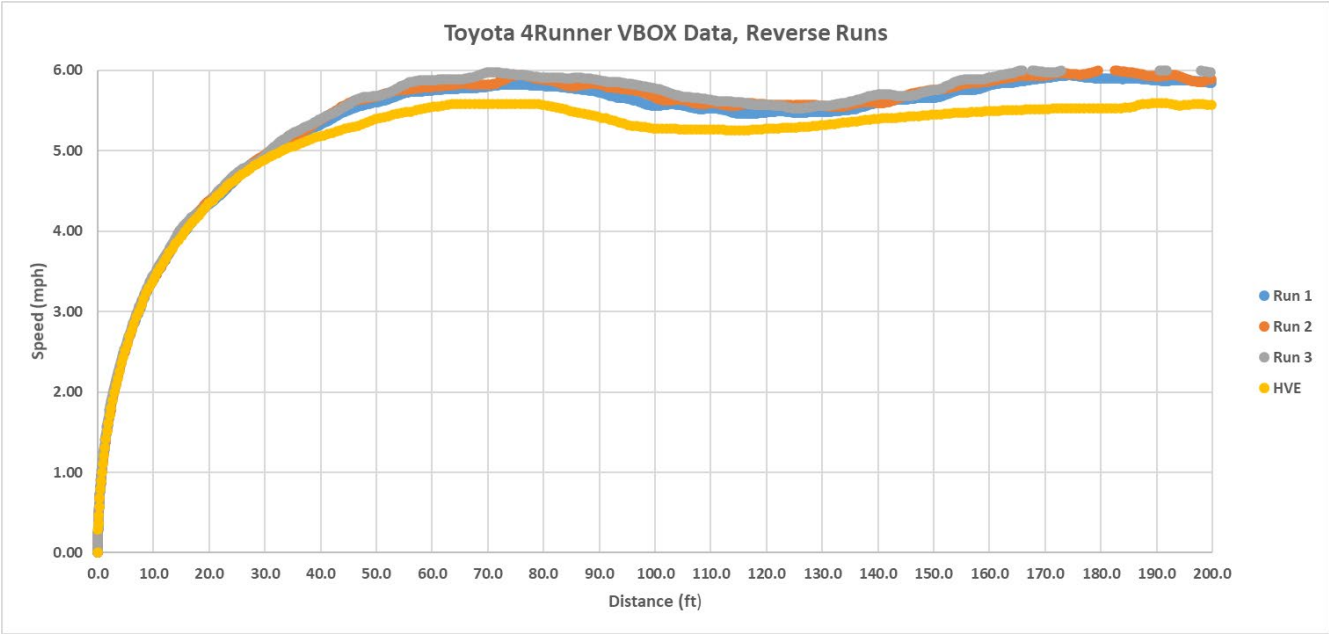

Mercury Mariner VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

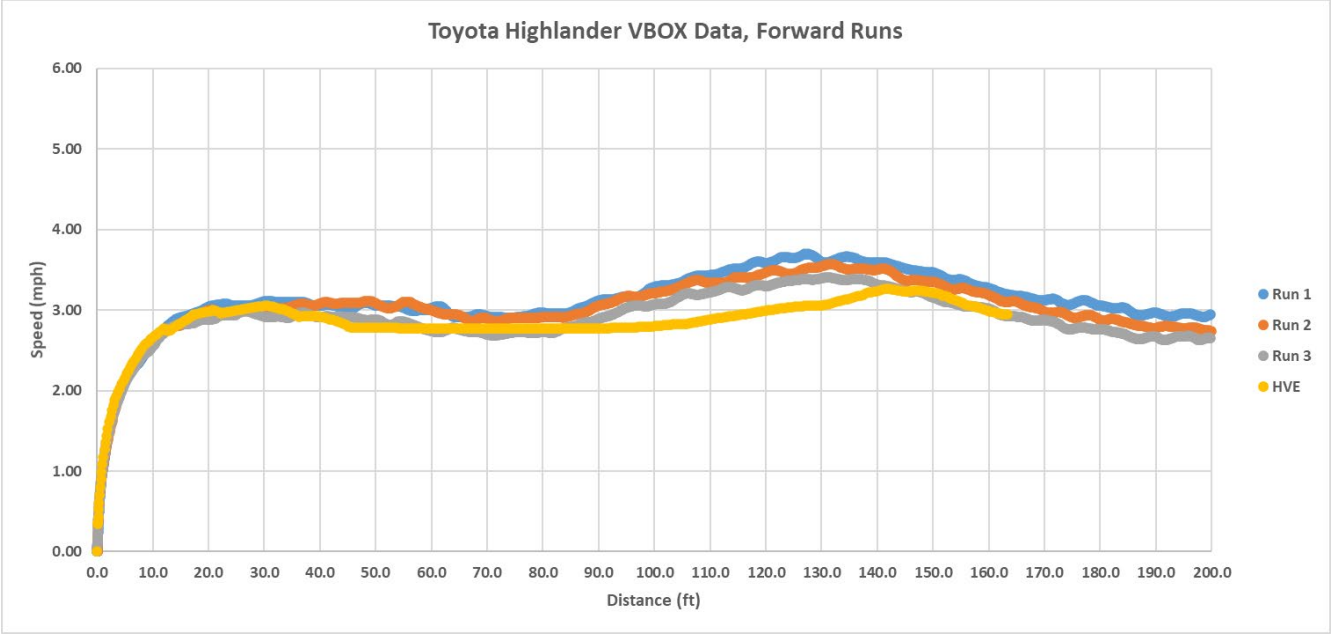

Mercury Mariner VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

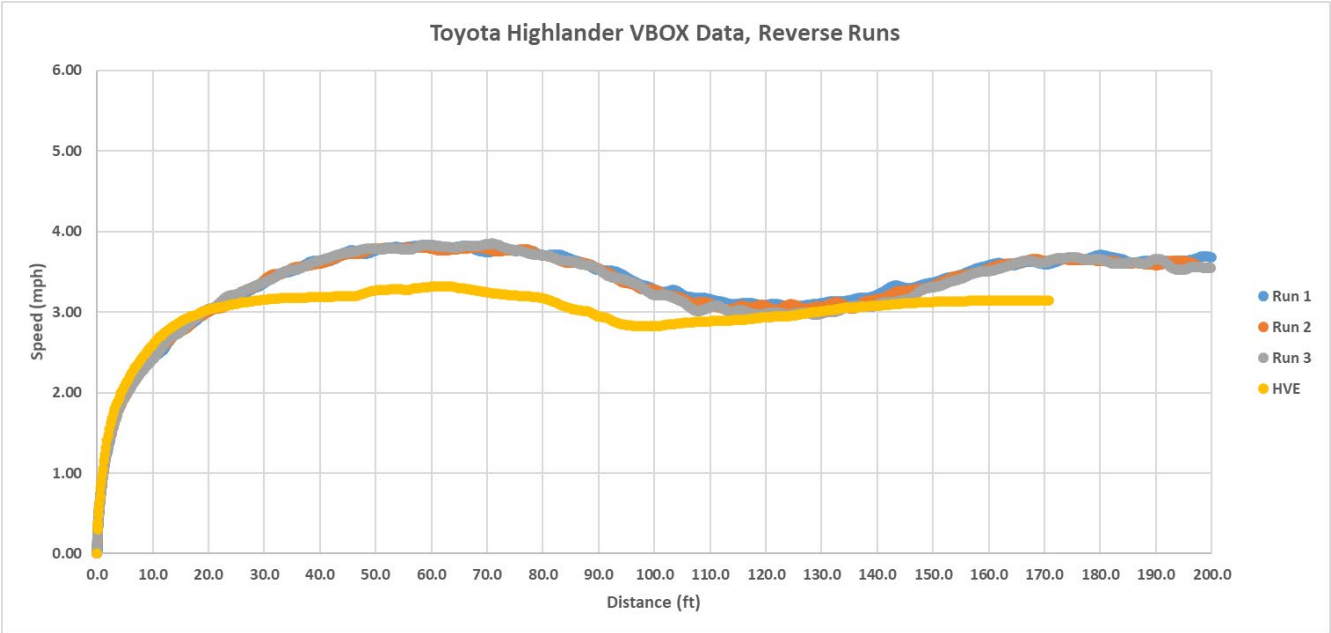

Toyota RAV4 VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

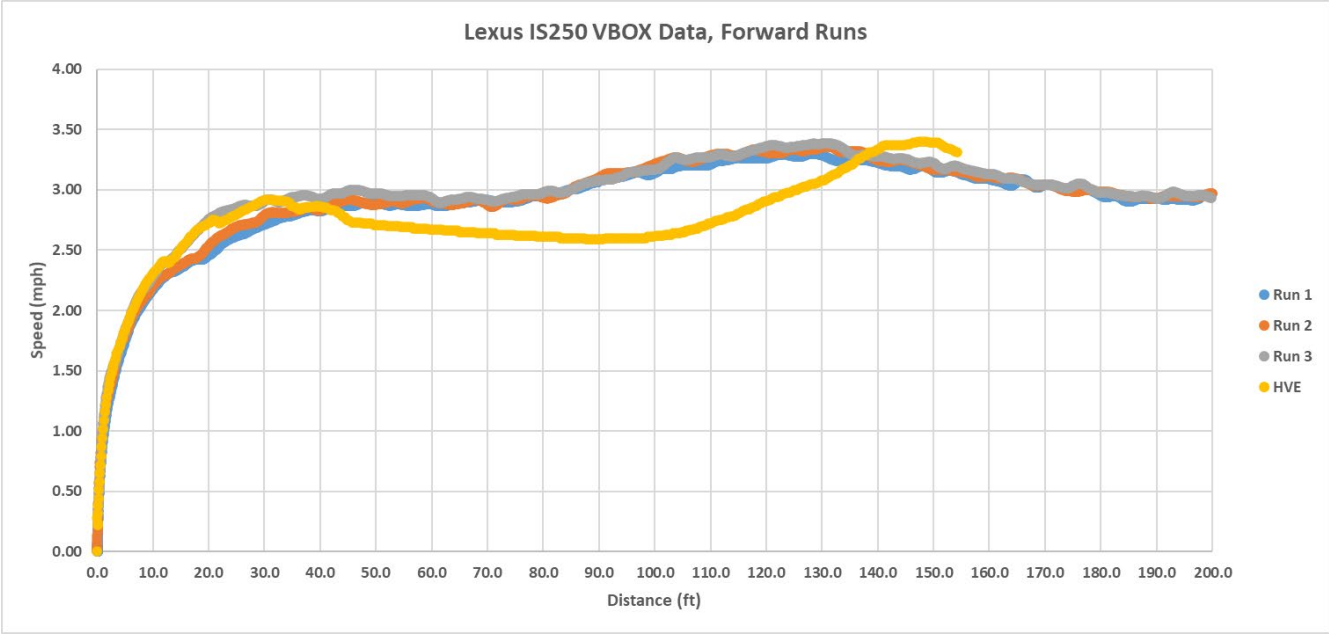

Toyota RAV4 VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

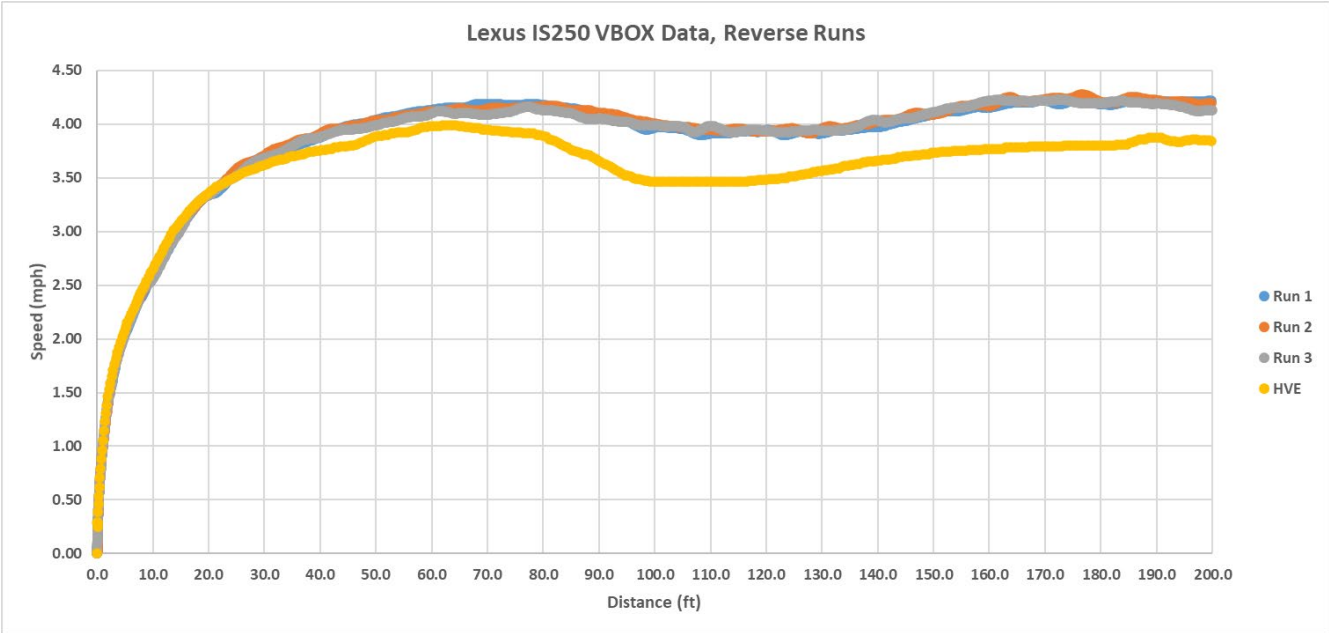

Toyota 4Runner VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

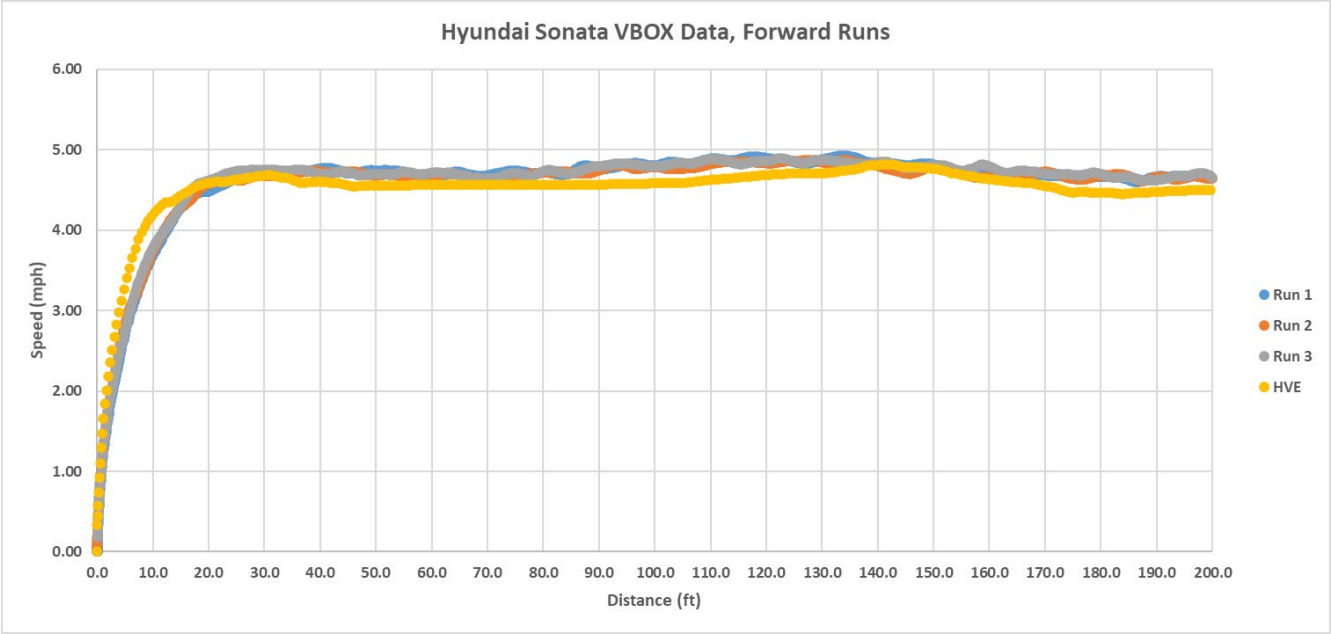

Toyota 4Runner VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

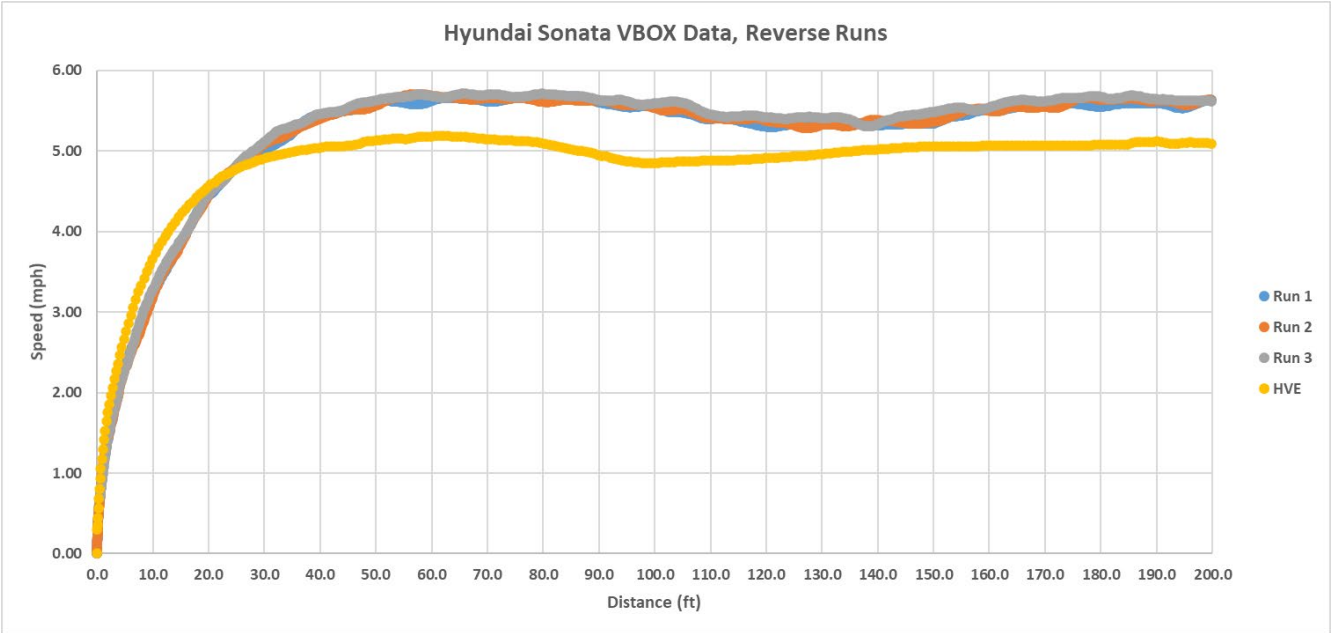

Toyota Highlander VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE


Toyota Highlander VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

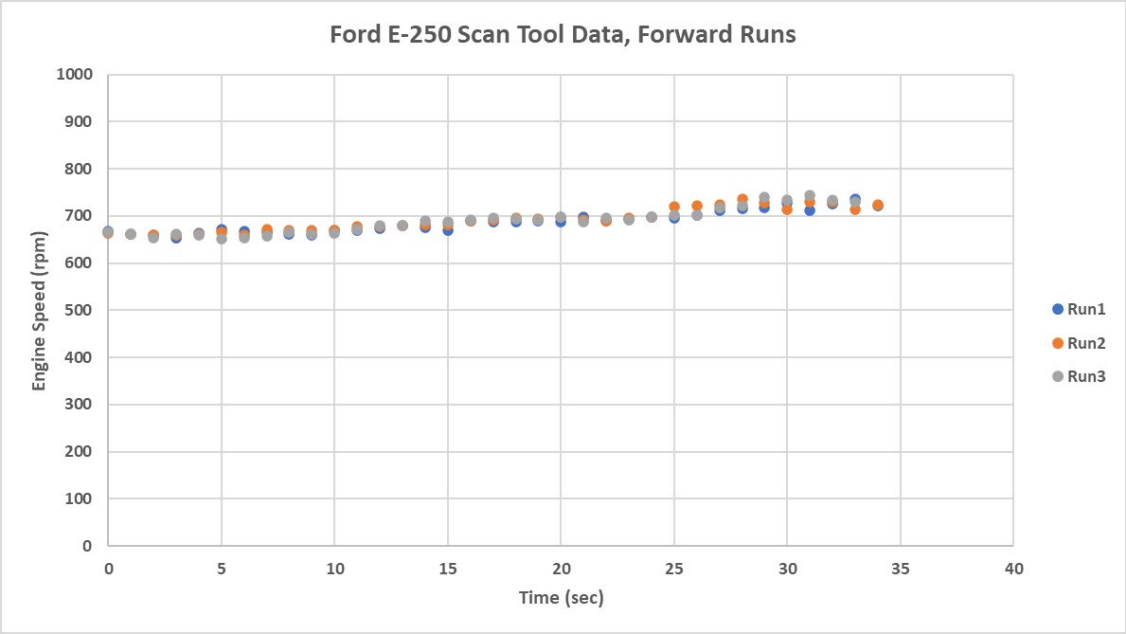

Lexus IS250 VBOX Data, Forward Runs
Speed (mph)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

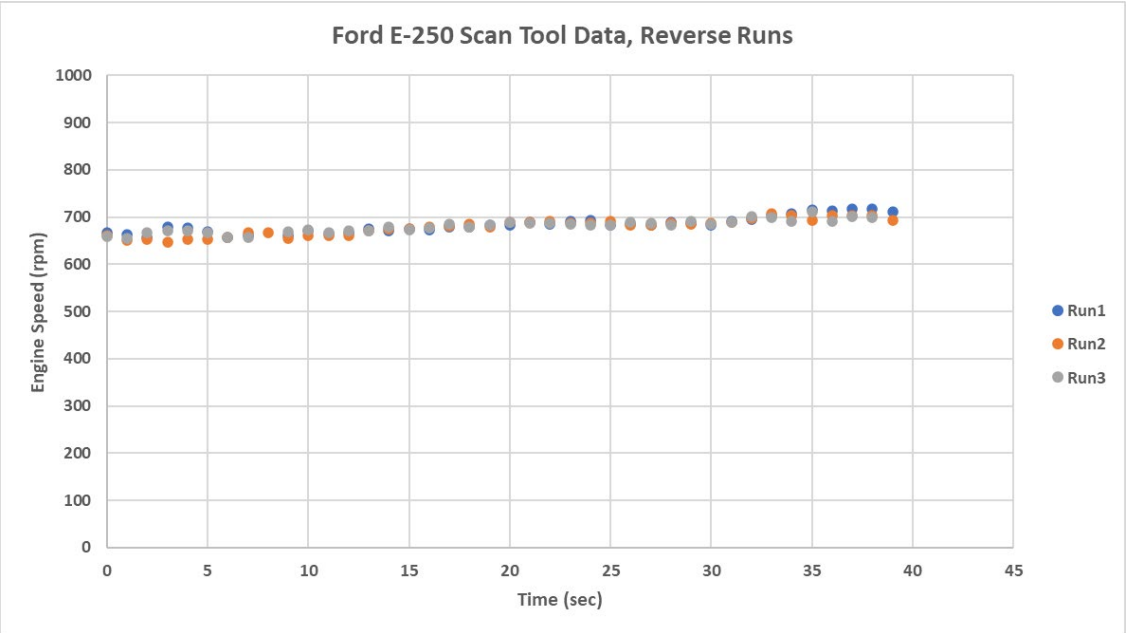

Lexus IS250 VBOX Data, Reverse Runs
Speed (mph)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

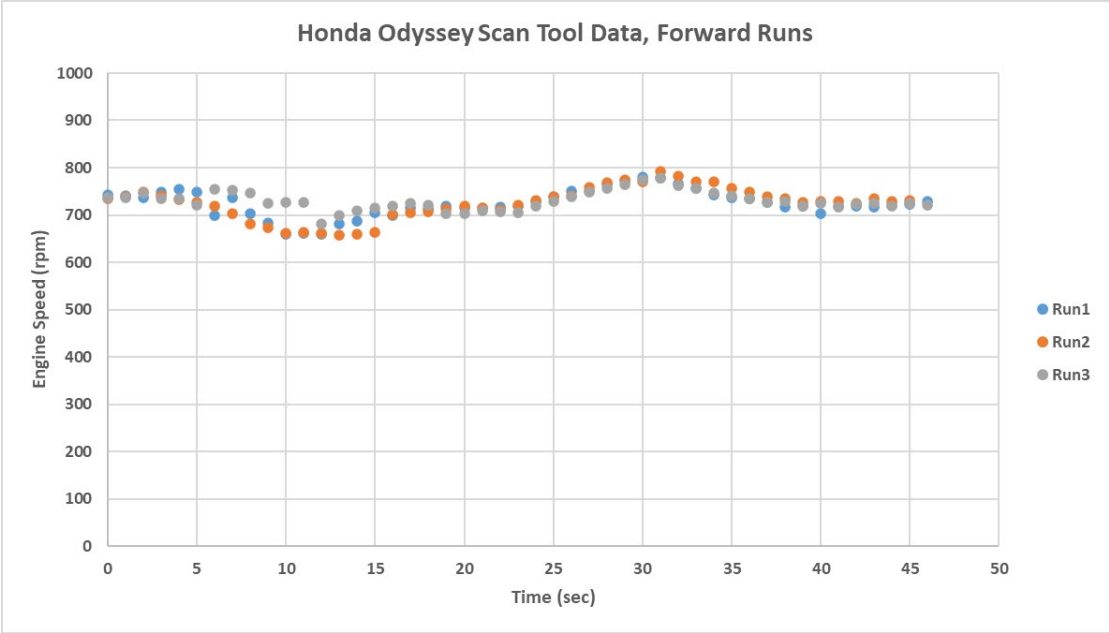

Hyundai Sonata VBOX Data, Forward Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

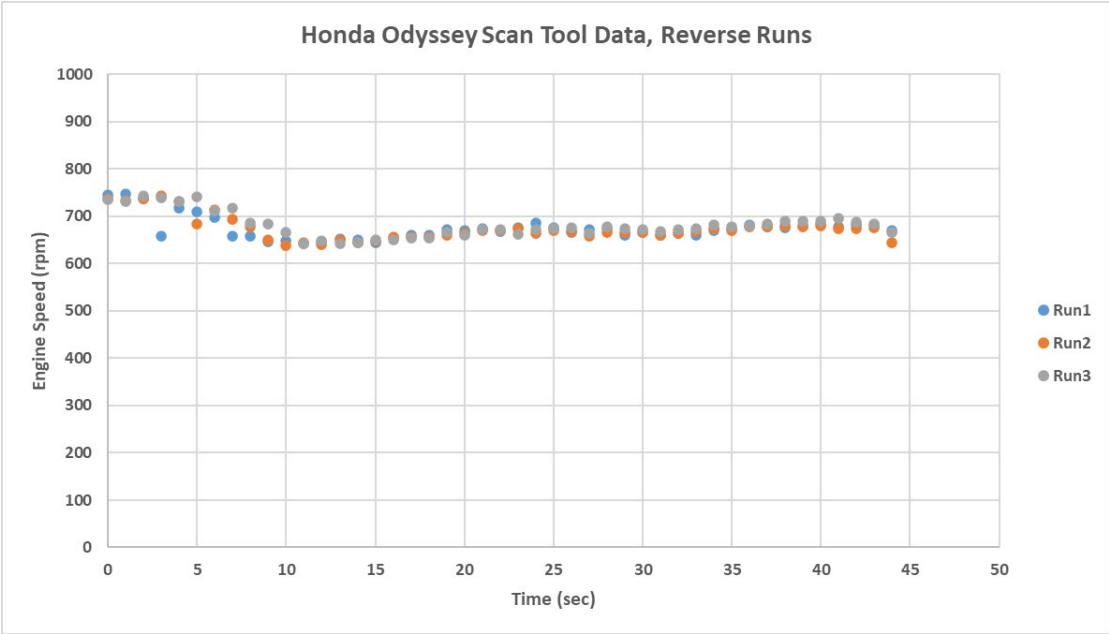

Hyundai Sonata VBOX Data, Reverse Runs
Speed (mph)
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
200.0
Distance (ft)
Run 1
Run 2
Run 3
HVE

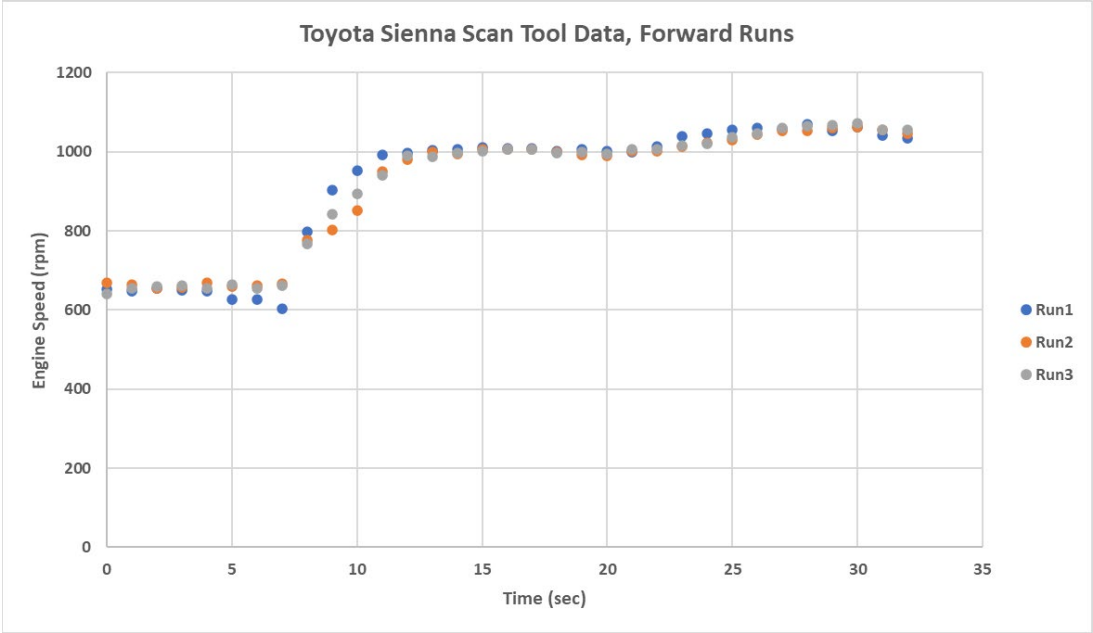
APPENDIX C

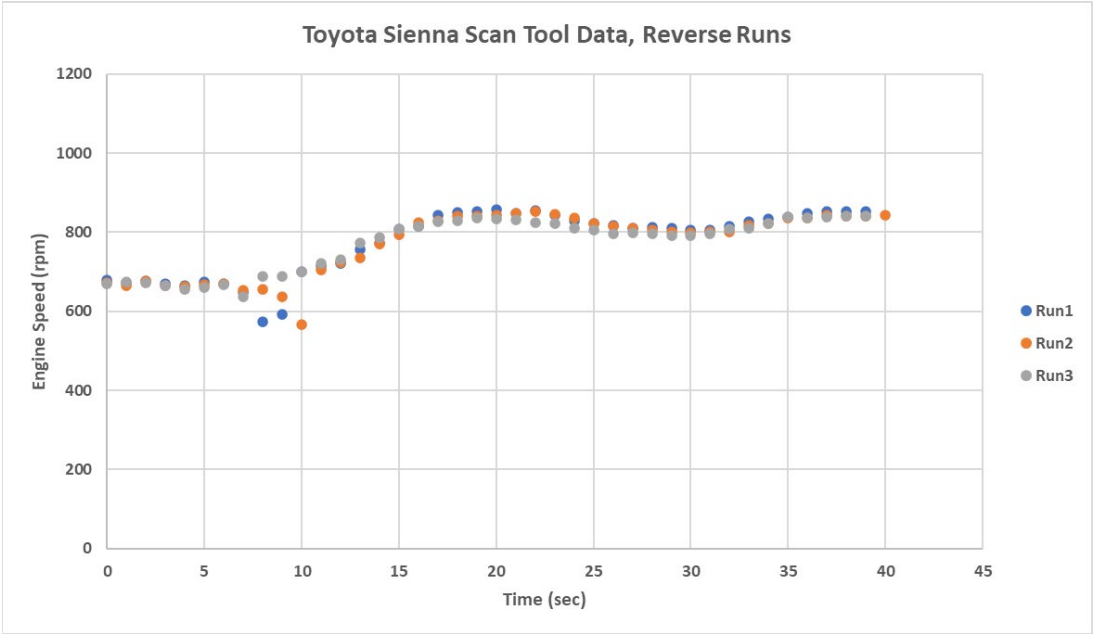

Ford E-250 Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
Time (sec)
Run1
Run2
Run3

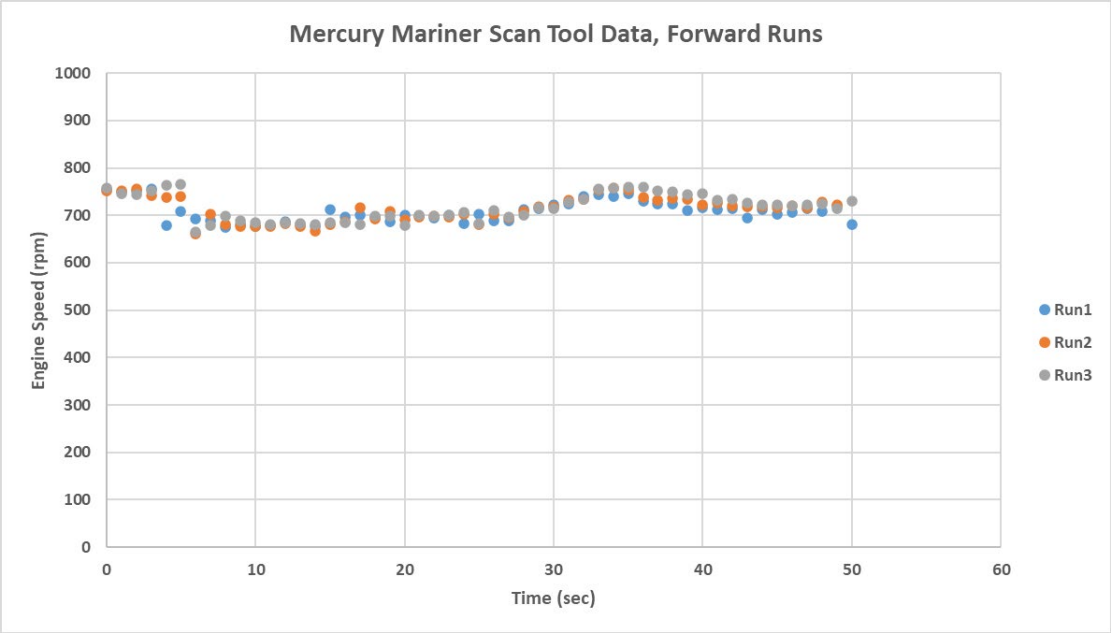

Ford E-250 Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
Time (sec)
Run1
Run2
Run3

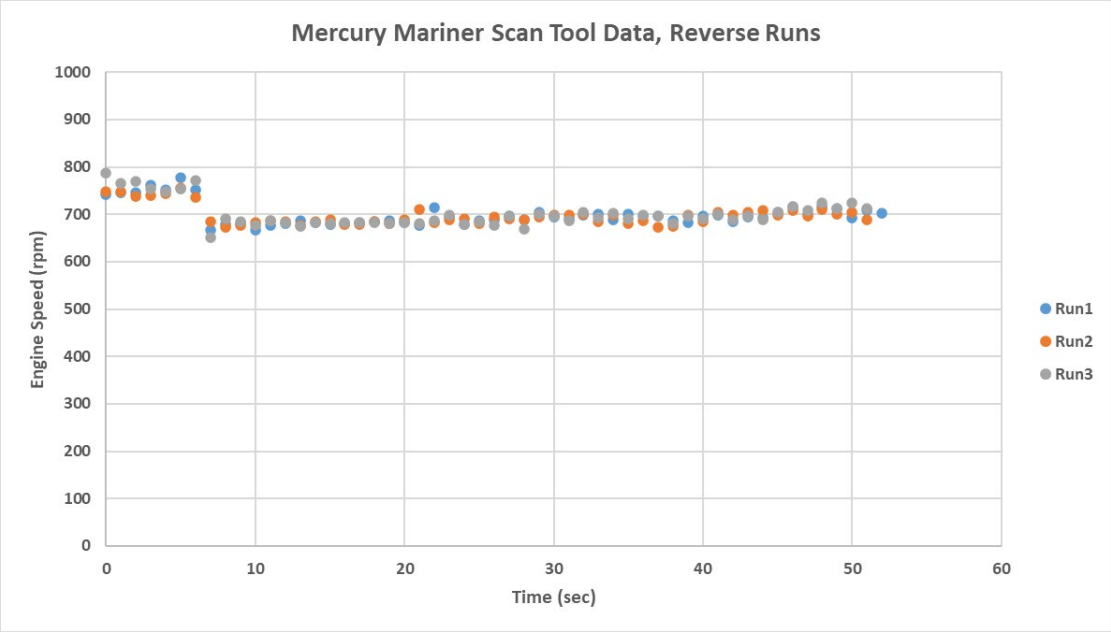

Honda Odyssey Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Time (sec)
Run1
Run2
Run3

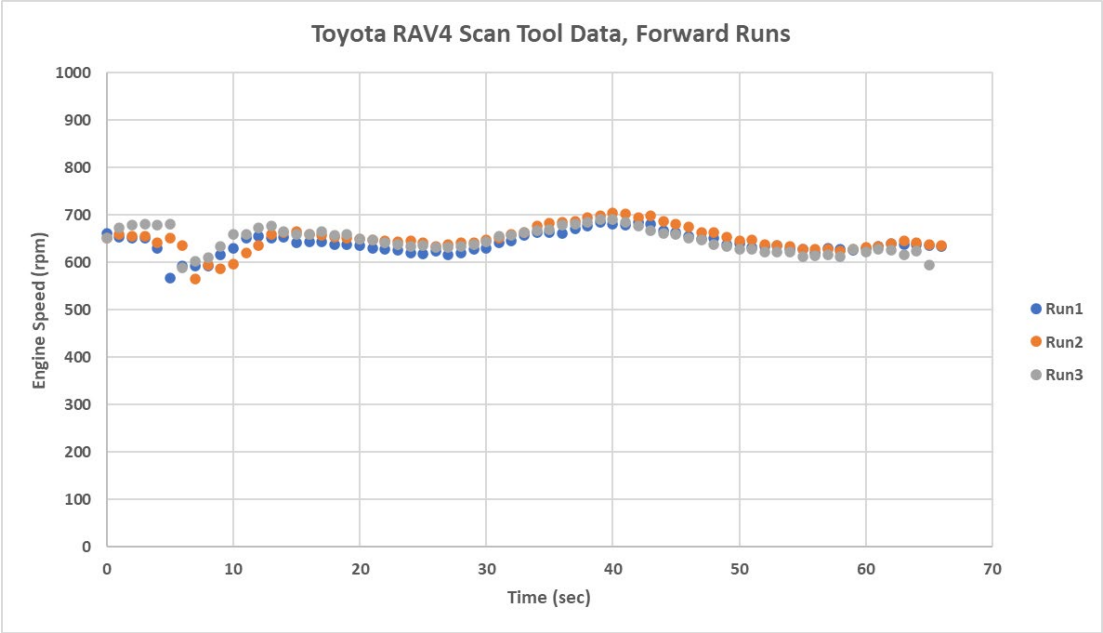

Honda Odyssey Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Time (sec)
Run1
Run2
Run3

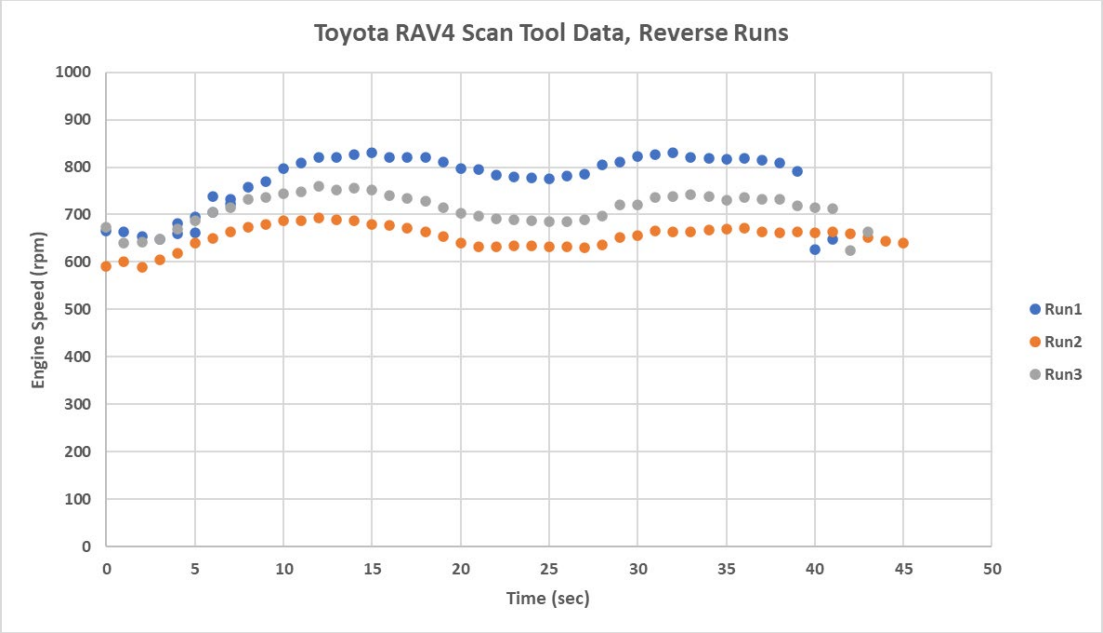

Toyota Sienna Scan Tool Data, Forward Runs
Engine Speed (rpm)
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
Time (sec)
Run1
Run2
Run3

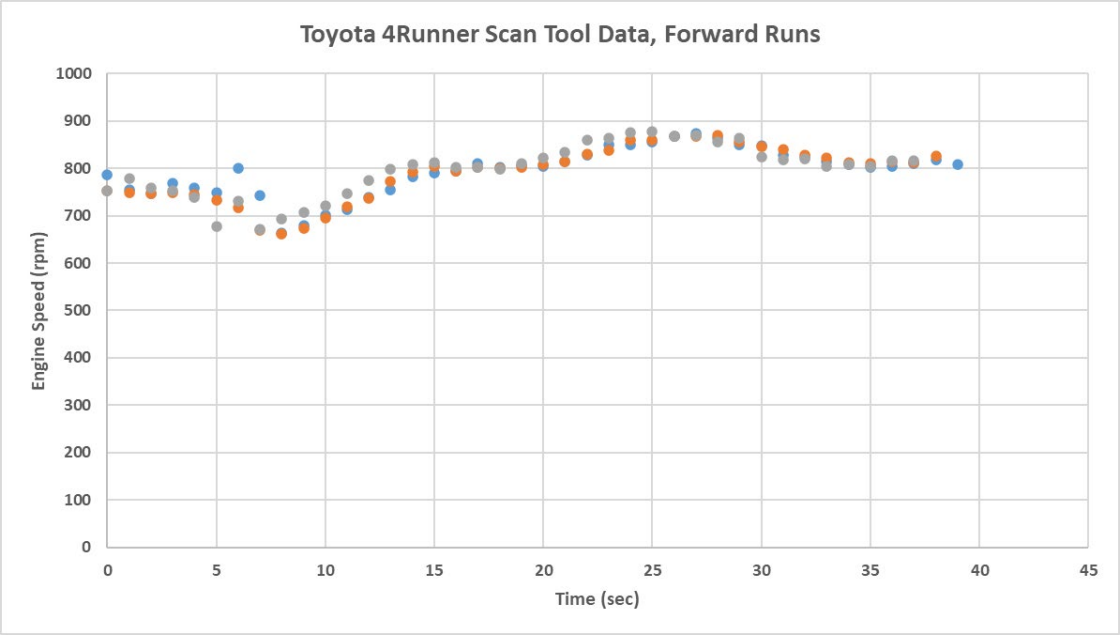

Toyota Sienna Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40
45
Time (sec)
Run1
Run2
Run3

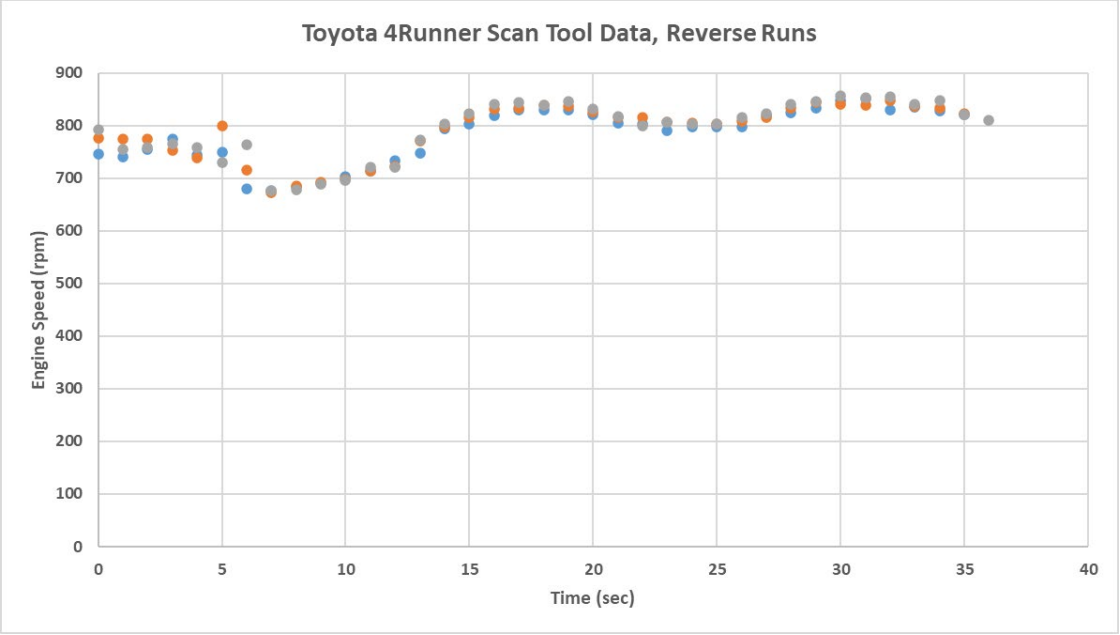

Mercury Mariner Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Time (sec)
Run1
Run2
Run3

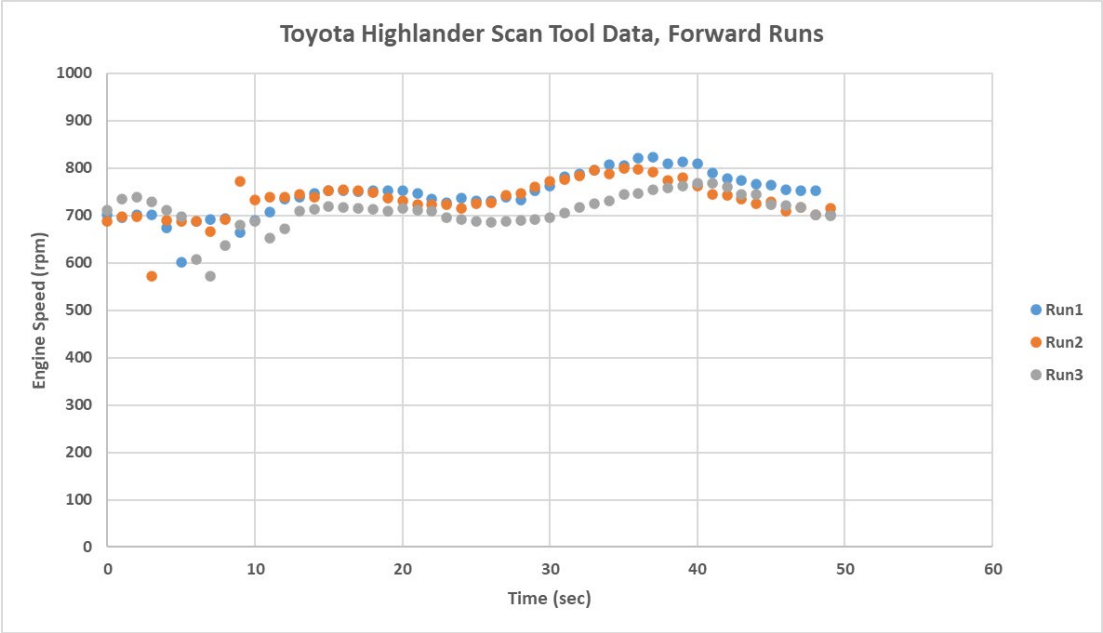

Mercury Mariner Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Time (sec)
Run1
Run2
Run3

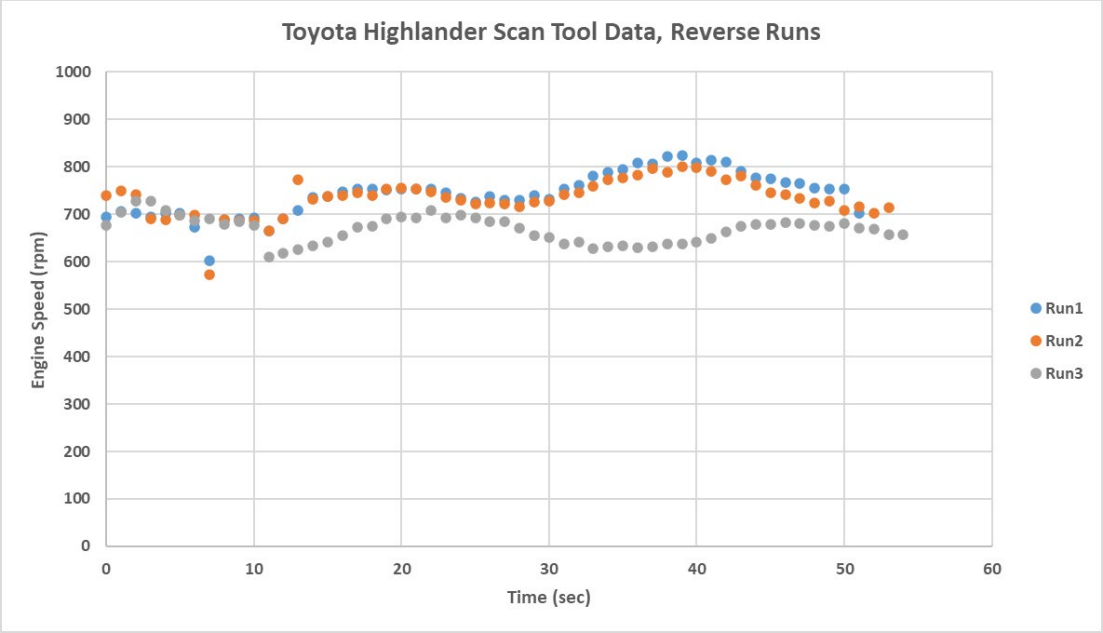

Toyota RAV4 Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
Time (sec)
Run1
Run2
Run3

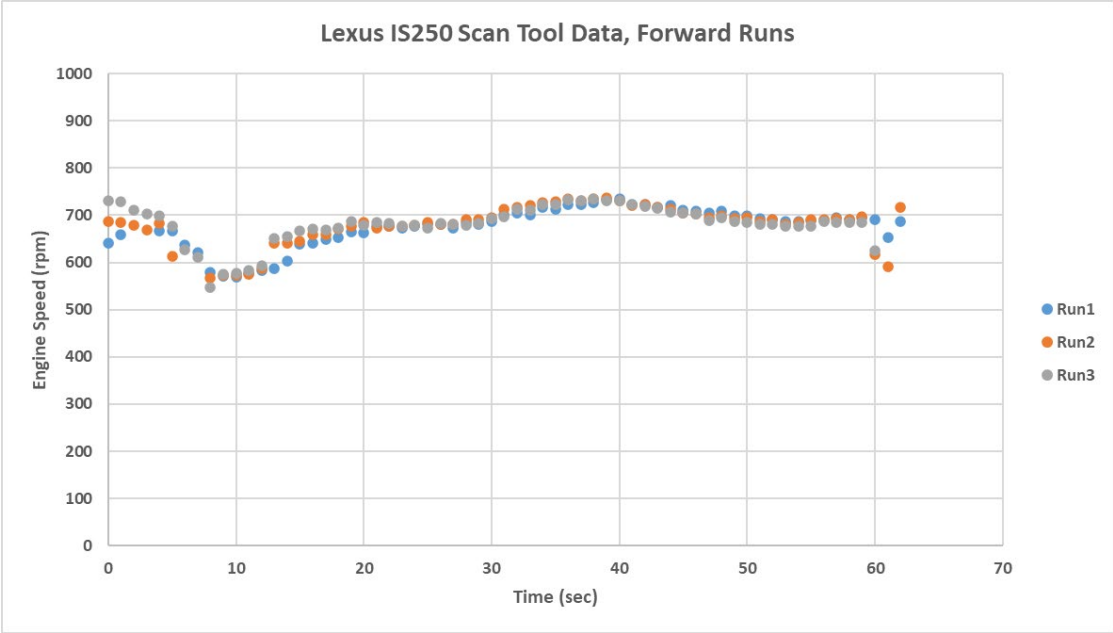

Toyota RAV4 Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Time (sec)
Run1
Run2
Run3

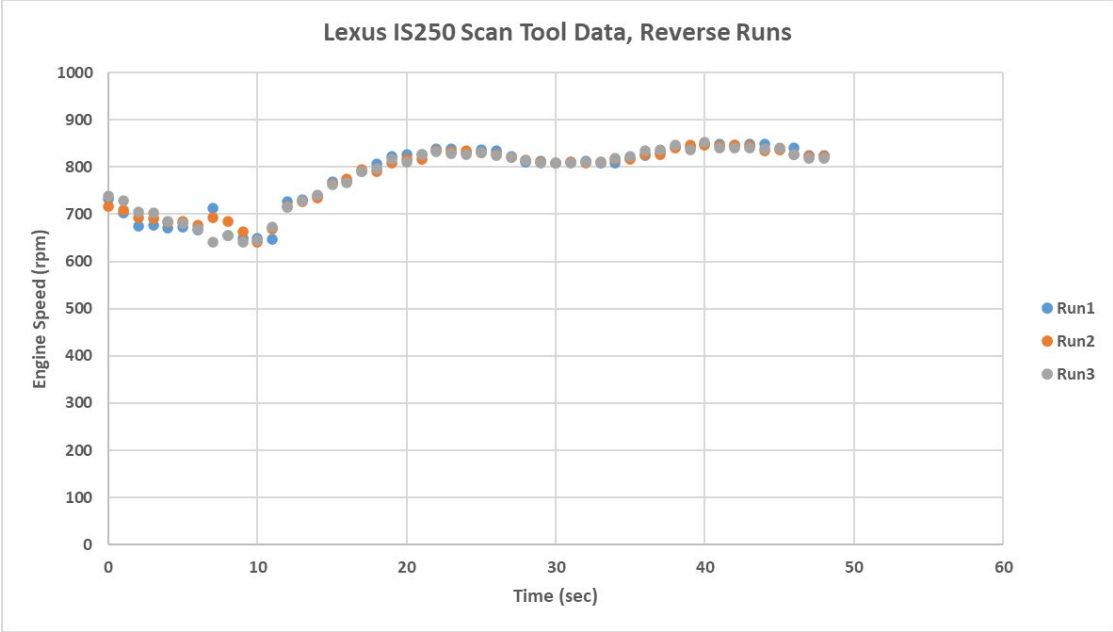

Toyota 4Runner Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
Time (sec)

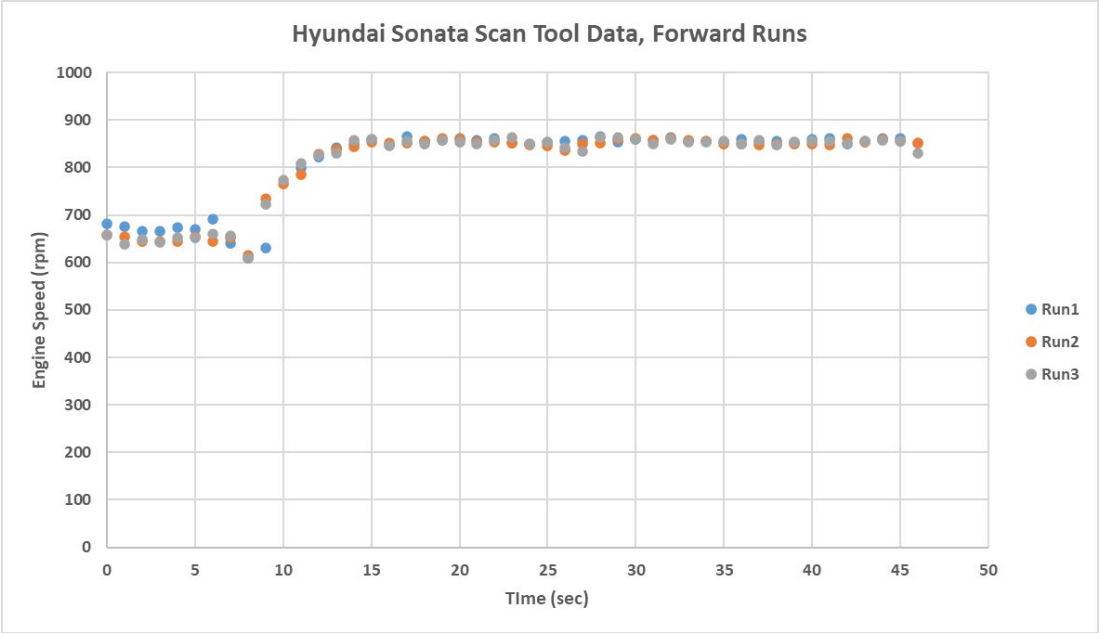

Toyota 4Runner Scan Tool Data, Reverse Runs
Engine Speed (rpm)
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
Time (sec)

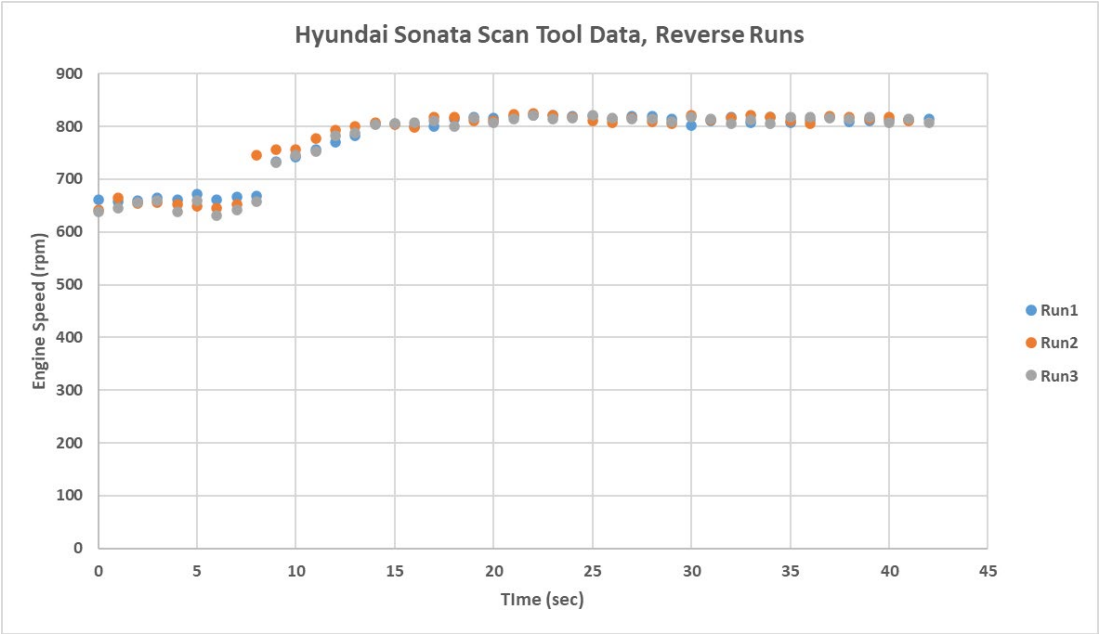

Toyota Highlander Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Time (sec)
Run1
Run2
Run3


Toyota Highlander Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Time (sec)
Run1
Run2
Run3


Lexus IS250 Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
Time (sec)
Run1
Run2
Run3


Lexus IS250 Scan Tool Data, Reverse Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Time (sec)
Run1
Run2
Run3


Hyundai Sonata Scan Tool Data, Forward Runs
Engine Speed (rpm)
1000
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
TIme (sec)
Run1
Run2
Run3


Hyundai Sonata Scan Tool Data, Reverse Runs
Engine Speed (rpm)
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
TIme (sec)
Run1
Run2
Run3