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Modeling of EV Performance for Drag Racing Optimization

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Summary

In the world of drag racing, it is desirable to be able to predict the performance of a vehicle, or more beneficially, to be able to model the performance of a vehicle, so as to design for the intended performance goals. An educational grant for a local high school automotive technology program to create a Pro Stock style drag race car prompted the development of a drag race performance simulation to aid in the design of the electric vehicle for improved performance.

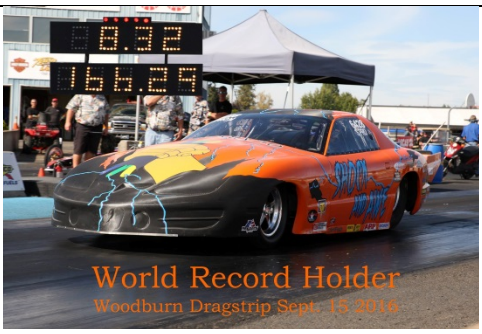

Figure1: Bothell High School AC Dragster – Shock and Awe

1 Drag Racing Background

1.1 Drag Racing Rules

Drag racing is a motorsport where two vehicles race next to each other in a straight line, accelerating from the starting line, with the goal of covering the required distance in as short a time as possible. The main sanctioning body for the sport of drag racing is the National Hot Rod Association (NHRA). Most drag racing competition happens over a distance of one quarter mile. The end result is an elapsed time (ET) that it took for the vehicle to cross the starting line light beam until it crossed the finish line light beam. The speed the vehicle was traveling at the finish line is also reported as the "trap speed" measured by measuring the time between the vehicle passing a light beam near the finish line, and passing the light beam at the finish line. Trap speed is a value of interest to drag racers, but the ET is the value that determines the winner of a race between two vehicles.

1.2 Drag Race Vehicle Description

Pro Stock is one category of drag racing within the National Hot Rod Association (NHRA). The vehicles in this class resemble production-based automobiles, but use a lightweight outer shell for the body made of fiberglass or carbon fiber and are built around a sophisticated tube chassis and four-link rear suspension.[1] Pro Stock vehicles also have openable doors, so they are often referred to as "door slammers" in the drag race community.

2 Project Background

The high dollar value of the grant to create a high power Pro Stock style drag race car allowed for the selection of the drivetrain to use high power AC motors, instead of a lower cost DC motor based drivetrain which has been typical for high performance electric vehicle drag racing. This electric drag race vehicle was to be one of the first very high performance and high voltage drag race vehicles to use AC motors, so there was not a historical knowledge base within the electric vehicle drag race community to easily estimate what the performance of this vehicle would be. This necessitated developing an electric vehicle drag race simulator. The drag race simulator takes in to account: the motor torque vs rpm curve, vehicle weight, vehicle aerodynamic drag, vehicle drivetrain drag, tire rolling resistance, rear differential gear ratio, and multiple shift-able gear ratios. The drag race simulator allowed for the informed selection of gear ratios and shift points to optimize performance while balancing with available and prudent gear ratios for this application. The electric drag race vehicle had data acquisition both from the AC motor inverter as well as from a standard drag racing data acquisition package from a manufacturer called Racepak, which allows for detailed comparison between the simulator and the actual racing results to fine tune the simulator for higher accuracy in the future. This vehicle is named "Shock and Awe" which the Northshore Automotive Technology program operated by Bothell High School teacher Pat McCue built and is raced b the teacher Pat. With a grant from foundry10, they had sufficient funds to use a high power AC motor based drivetrain rather than a much more affordable DC motor based drivetrain for a similar power output.

3 Drivetrain

The motor drivetrain consists of two Delco Remy motors specially modified by AM Racing of Hood River, Oregon, to be mated end to end as a dual core motor, model AMR-Remy DC115R. They are powered by two Rinehart PM250 DZ motor inverters manufactured by Rinehart Motion Systems of Wilsonville, Oregon. Each inverter is capable of supplying 600 A rms peak, and can operate at up to 800 VDC maximum input voltage. The power to the two inverters is supplied by a battery pack of power lithium polymer battery cells supplied by Lonestar EV Conversions of Humble, Texas. Power cells are designed for high current and power output, and thus high power density or power per unit of weight, whereas capacity cells are designed for higher energy density. The battery pack cells are arranged in modules that are made of four cells in parallel, and the modules are arranged 192 in series, for a nominal voltage of 710 VDC, and a fully charged voltage of 800 VDC.

4 Drag Racing Simulator

4.1 Simulator Overview

The drag racing simulator was created in Microsoft Excel using the inputs listed above in the Project Background section (the motor torque vs rpm curve, vehicle weight, vehicle aerodynamic drag, vehicle drivetrain drag, tire rolling resistance, rear differential gear ratio, and multiple shift-able gear ratios), and performing a series of incremental calculations in small time steps, and using the speed output from each time step as the input of the next time step. A portion of the drag racing simulator is shown below in Table 1 which displays the summary at the top of the table with the pertinent quarter mile results highlighted in green, and a portion of the calculation table displayed at the bottom. Cells which require a user entered input are highlighted in yellow. The simulator takes named inputs which are entered to the right of each cell with a "name code", and then uses a VLOOKUP function to fill in data in each of the cells below it which have no yellow highlighting. Each vertical section of the summary table such as "vehicle name code" or "transmission name code" have data in their own worksheet of the Excel file which the

VLOOKUP function references to fill in the rest of the data for that vertical section. Time steps of 0.01 seconds and 0.1 seconds were tested, with less than 1% difference in the elapsed time output and less than 0.01% difference in the trap speed output, so 0.1 second time steps were used to make the data table more meaningful by being able to see significant changes in values within the viewing area of a screen or paper. The simulator is able to model up to four two-speed transmission segments coupled together, but in the initial version of this vehicle, it only uses a single two-speed transmission. The simulator is able to model the shifting of gears and the result that has on the vehicle's acceleration and speed throughout the drag race.

Table 1: Screen Capture of Portion of Drag Racing Simulator

EV Performance Calculator

Project Name: Bothell High School dragster - Shock and Awe

created by Ron Easley
date created: 3/2/2015
last revised: 1/17/2017

key:	
(yellow)	.... manual user input
(green)	.... calculated output

Drag Racing Simulator

											transmission # 1st	2nd	3rd	4th			
vehicle name code	BHSD	battery name code	LEV_SC	motor name code	AMR_DC115R	controller name code	R_250R	differential name code	PTRE_357	transmission name code	PG_BTE_198				final drive ratio	tire name code	MT33_5
vehicle weight (kg)	828.27	# in series	190	operating voltage (Vrms)	600	peak current (Arms)	600	gear ratio	3.57	1st gear ratio	1.98	1.00	1.00	1.00	7.07	diameter (m)	0.856
frontal area (m^2)	1.92	# in parallel	4	weight (kg)	63.50	max operating voltage (VDC)	720	Cdt	0.003	2nd gear ratio	1.00	1.00	1.00	1.00	3.57	Crr	0.03
coefficient of drag (Cd)	0.34	peak load voltage (V)	636.4	max rpm	10,000	weight (kg)	36.29			3rd gear ratio	0.00	1.00	1.00	1.00	0.00	Cf	4
		peak current (A)	1,200							4th gear ratio	0.00	1.00	1.00	1.00	0.00	rear weight %	58%
		weight (kg)	99.79							5th gear ratio	0.00	1.00	1.00	1.00	0.00		

driver weight (lb)	200	air density (kg/m^3)	1.21
driver weight (kg)	90.72	time step (sec.)	0.1
total weight (kg)	1,119		
static friction force (N)	43,893		

60 ft time (sec.)	1.7
0-60 mph time (sec.)	2.2

1/8 mile time (sec.)	5.9
1/8 mile speed (mph)	135.38

1/4 mile time (sec.)	8.9
1/4 mile speed (mph)	164.35

time (sec.)	speed (m/s)	speed (mph)	tire rpm	cumulative distance (m)	cumulative distance (ft)	gear used	motor rpm	motor torque (Nm)	applied force (N)	aerodynamic drag force (N)	drivetrain drag force (N)	rolling resistance drag force (N)	total drag force (N)	net force (N)	net acceleration (m/s^2)	g force	tire slip?	time (sec.)	speed (mph)
0	0	0.00	0.00	0.00	0.00	1st gear	0	823.5	13,601	0.00	0.00	329.20	329.20	13,272	11.86	1.21	NO	0	0.00
0.1	1.19	2.65	26.47	0.12	0.39	1st gear	187.12	823.5	13,601	0.56	3.98	329.20	333.73	13,267	11.86	1.21	NO	0.1	2.65
0.2	2.37	5.31	52.94	0.36	1.17	1st gear	374.18	823.5	13,601	2.23	7.96	329.20	339.38	13,261	11.86	1.21	NO	0.2	5.31
0.3	3.56	7.96	79.39	0.71	2.34	1st gear	561.17	823.5	13,601	5.01	11.94	329.20	346.14	13,255	11.85	1.21	NO	0.3	7.96

quarter mile simulator_6.2 | **quarter mile simulator_3.57** | vehicle info | speed vs time_3.57 | distance vs time_3.57 | torque vs time_3.57 | net accel. vs tim

4.2 Simulator Input Constants for Shock and Awe

The input constants for the drag race vehicle Shock and Awe and the simulation are: total weight of 1,119 kg, frontal area of 1.92 m^2, coefficient of drag (C_d) of 0.34, maximum motor revolutions per minute (rpm) of 10,000, rear differential gear ratio of 3.57, rear differential coefficient of drag (C_{dt}) of 0.003, transmission 1st gear ratio of 1.98, transmission 2nd gear ratio of 1.00, tire diameter of 0.856 m, tire coefficient of rolling resistance (C_{rr}) of 0.03, tire coefficient of static friction (C_f) of 4, rear weight percentage of 58%, air density of 1.21 kg/m^3, and time step of 0.1 second increments. These can be seen below in Table 2.

Table 2: Screen Capture of Drag Racing Simulator Summary Table

Drag Racing Simulator

											transmission # 1st	2nd	3rd	4th			
vehicle name code	BHSD	battery name code	LEV_SC	motor name code	AMR_DC115R	controller name code	R_250R	differential name code	PTRE_357	transmission name code	PG_BTE_198				final drive ratio	tire name code	MT33_5
vehicle weight (kg)	828.27	# in series	192	operating voltage (Vrms)	600	peak current (Arms)	600	gear ratio	3.57	1st gear ratio	1.98	1.00	1.00	1.00	7.07	diameter (m)	0.856
frontal area (m^2)	1.92	# in parallel	4	weight (kg)	63.50	max operating voltage (VDC)	720	Cdt	0.003	2nd gear ratio	1.00	1.00	1.00	1.00	3.57	Crr	0.03
coefficient of drag (Cd)	0.34	peak load voltage (V)	636.4	max rpm	10,000	weight (kg)	36.29			3rd gear ratio	0.00	1.00	1.00	1.00	0.00	Cf	4
		peak current (A)	1,200							4th gear ratio	0.00	1.00	1.00	1.00	0.00	rear weight %	58%
		weight (kg)	99.79							5th gear ratio	0.00	1.00	1.00	1.00	0.00		

driver weight (lb)	200	air density (kg/m^3)	1.21
driver weight (kg)	90.72	time step (sec.)	0.1
total weight (kg)	1,119		
static friction force (N)	43,893		

60 ft time	1.7
0-60 mph time	2.2

1/8 mile time	5.9
1/8 mile speed	135.38

1/4 mile time	8.9
1/4 mile speed	164.35

The total weight is a sum of the vehicle weight, battery weight, motor weight, controller weight, and driver weight.

4.2.1 Coefficient of Rolling Resistance

The coefficient of rolling resistance (C_{rr}) value of 0.03 for large diameter drag slick tires is an estimated value determined from seeing estimates from drag racing forums and is substantially higher, as expected due to their soft rubber and low inflation pressure, than the typical values for passenger car tires on concrete or new asphalt of 0.01 to 0.015.[3]

4.2.2 Rear Differential Coefficient of Drag

The rear differential coefficient of drag (C_{dt}) of 0.003 is an estimated value for Shock and Awe that was calculated from a coast down test of a similar weight, manual transmission, passenger car since it was not practical to perform a similar test on Shock and Awe before it was constructed. This value in the Drag Race Simulator is a total value for all of the mechanical drivetrain components combined, including the rear differential, the transmission, and bearings. The coast down test was conducted by letting the vehicle coast from 60 miles per hour (mph) down to 5 mph on a straight, fairly flat section of road, conducting three trials in each direction in a short span of time and recording the time in 5 mph increments from a video of the speedometer, and averaging all of the trials together. A polynomial regression was performed in Microsoft Excel on the plot of the average speed over time to determine the deceleration over time. The aerodynamic drag was calculated and plotted in Microsoft Excel as a function of vehicle speed using Equation (1) below.

$$F_d = \frac{1}{2} C_d A \rho v^2 \qquad [4](1)$$

Where F_d is the aerodynamic drag force, C_d is the coefficient of drag of the vehicle, A is the frontal area of the vehicle, ρ is the density of air, and v is the velocity of the vehicle. The aerodynamic force was converted in to a deceleration value using the mass of the vehicle m. The coefficient of rolling resistance (C_{rr}) was calculated using Equation (2) below.

$$F_{rr} = C_{rr} m g \qquad [5](2)$$

Where F_{rr} is the rolling resistance force, C_{rr} is the coefficient of rolling resistance, m is the mass of the vehicle, and g is the acceleration of gravity. The rolling resistance force was converted in to a deceleration value using the mass of the vehicle m. Then the aerodynamic drag deceleration as a function of velocity and the rolling resistance deceleration were subtracted from the plot of the average total deceleration and another polynomial regression was performed on the result to determine the drivetrain coefficient of drag (C_{dt}). The R^2 values for each polynomial regression were greater than 0.9892. This value for C_{dt} of 0.003 is what was used for the differential coefficient of drag for Shock and Awe as an approximation.

4.3 Simulator Time Step Numerical Calculations

In the drag race simulator, the initial conditions at time equals zero are that the speed, tire rpm, cumulative distance travelled, and motor rpm are zero. Electric motors can produce maximum torque at zero rpm, as does the dual electric motors in Shock and Awe, so the torque is the value from the plot of maximum torque vs rpm in the following graph in Figure 2.

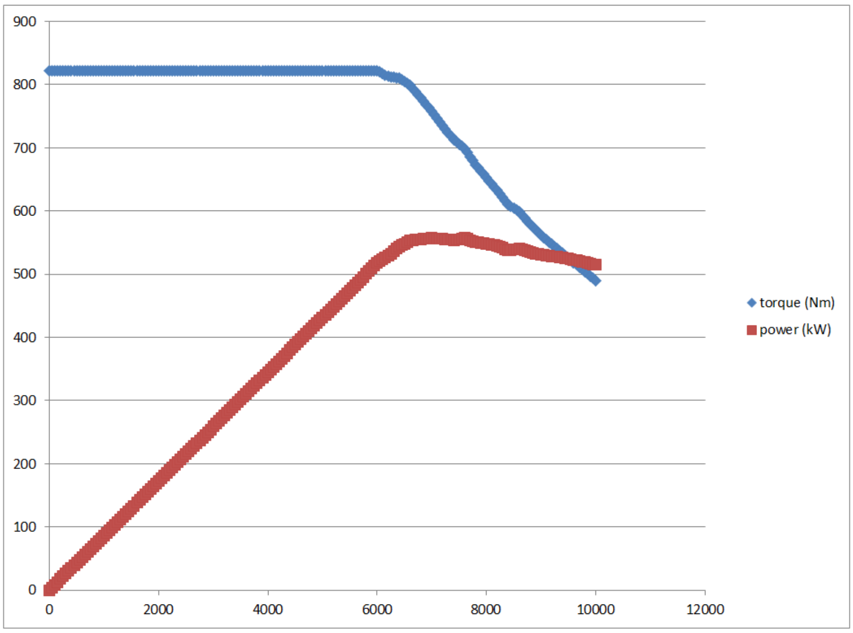

Figure 2: AMR-Remy DC115R Motor Torque and Power vs rpm Curves

At time equals zero, the maximum torque of the motor is determined from a VLOOKUP function using the worksheet with the source data for the motor torque curve, and the applied force to the ground is calculated using Equation (3) below.

$$F_a = \frac{TR_{fd}}{D/2} \tag{3}$$

Where F_a is the applied force to the ground, T is the torque of the motor, R_{fd} is the final drive ratio of the differential ratio multiplied by the transmission gear ratio, and D is the diameter of the tire. The speed of the vehicle at time step 2 is calculated by subtracting the rolling resistance force from the applied force from Equation (3), and dividing by the mass of the vehicle to calculate the net acceleration, and multiplying it by the time step of 0.1 seconds. The calculated speed at time step 2 is then used as the input for calculating the distance travelled between time step 1 and 2, calculating the tire rpm, calculating the motor rpm, and then using the VLOOKUP function to return the motor torque value. From time step 2 and onward, there are additionally aerodynamic forces and drivetrain drag forces in addition to the rolling resistance force. All three of these resistance forces are subtracted from the applied force to determine the net acceleration and the resultant speed for the next time step. These calculations are done independently for each gear, and then a set of nested IF-THEN statements are used to compare the applied force of the tires to the ground for each gear, and choose to upshift gears when the applied force of second gear exceeds that of first gear, or when the maximum rpm of the motor is reached in first gear. Table 3 below shows some of the resultant calculations for the speed, tire rpm, cumulative distance, and the motor rpm, torque, and applied force for each gear. Note that there is no data for third gear from time step 2 and onward because there is no data for a third gear populated in the summary table since Shock and Awe only has two gears.

Table 3: Screen Capture of Drag Racing Simulator Time Step Numerical Calculations for Each Gear

						1st gear			2nd gear			3rd gear		
time (sec.)	speed (m/s)	speed (mph)	tire rpm	cumulative distance (m)	cumulative distance (ft)	motor rpm	torque (Nm)	applied force (N)	motor rpm	torque (Nm)	applied force (N)	motor rpm	torque (Nm)	applied force (N)
0	0	0.00	0.00	0.00	0.00	0.00	823.5	13,601	0.00	823.5	6,869	0.00	823.5	0
0.1	1.19	2.65	26.47	0.12	0.39	187.12	823.5	13,601	94.51	823.5	6,869	0.00	0	0
0.2	2.37	5.31	52.94	0.36	1.17	374.18	823.5	13,601	188.98	823.5	6,869	0.00	0	0
0.3	3.56	7.96	79.39	0.71	2.34	561.17	823.5	13,601	283.42	823.5	6,869	0.00	0	0
0.4	4.74	10.61	105.83	1.19	3.89	748.05	823.5	13,601	377.80	823.5	6,869	0.00	0	0
0.5	5.93	13.26	132.25	1.78	5.84	934.83	823.5	13,601	472.13	823.5	6,869	0.00	0	0
0.6	7.11	15.91	158.66	2.49	8.17	1,121.47	823.5	13,601	566.40	823.5	6,869	0.00	0	0
0.7	8.29	18.55	185.04	3.32	10.89	1,307.98	823.5	13,601	660.60	823.5	6,869	0.00	0	0
0.8	9.47	21.20	211.40	4.27	14.00	1,494.33	823.5	13,601	754.71	823.5	6,869	0.00	0	0
0.9	10.66	23.84	237.74	5.33	17.49	1,680.50	823.5	13,601	848.74	823.5	6,869	0.00	0	0
1	11.83	26.48	264.05	6.52	21.38	1,866.49	823.5	13,601	942.67	823.5	6,869	0.00	0	0
1.1	13.01	29.11	290.34	7.82	25.65	2,052.27	823.5	13,601	1,036.50	823.5	6,869	0.00	0	0
1.2	14.19	31.74	316.59	9.24	30.30	2,237.84	823.5	13,601	1,130.22	823.5	6,869	0.00	0	0
1.3	15.36	34.37	342.81	10.77	35.34	2,423.17	823.5	13,601	1,223.82	823.5	6,869	0.00	0	0
1.4	16.54	37.00	368.99	12.43	40.77	2,608.25	823.5	13,601	1,317.30	823.5	6,869	0.00	0	0
1.5	17.71	39.62	395.14	14.20	46.58	2,793.06	823.5	13,601	1,410.64	823.5	6,869	0.00	0	0
1.6	18.88	42.24	421.24	16.08	52.77	2,977.60	823.5	13,601	1,503.84	823.5	6,869	0.00	0	0
1.7	20.05	44.85	447.31	18.09	59.35	3,161.84	823.5	13,601	1,596.89	823.5	6,869	0.00	0	0
1.8	21.21	47.46	473.33	20.21	66.31	3,345.78	823.5	13,601	1,689.79	823.5	6,869	0.00	0	0
1.9	22.38	50.06	499.31	22.45	73.65	3,529.39	823.5	13,601	1,782.52	823.5	6,869	0.00	0	0
2	23.54	52.66	525.23	24.80	81.37	3,712.66	823.5	13,601	1,875.08	823.5	6,869	0.00	0	0
2.1	24.70	55.26	551.11	27.27	89.48	3,895.58	823.5	13,601	1,967.46	823.5	6,869	0.00	0	0
2.2	25.86	57.85	576.94	29.86	97.96	4,078.13	823.5	13,601	2,059.66	823.5	6,869	0.00	0	0

Table 4 below shows the calculated values for the selected gear that the vehicle is in as well as each drag force, the net force, the net acceleration, the g force, whether there is tire slippage due to the g force exceeding the static coefficient of friction (C_f) of the drag slick on a drag race track, and the time step and speed.

Table 4: Screen Capture of Drag Racing Simulator Time Step Numerical Calculations for Net Acceleration

gear used	motor rpm	motor torque (Nm)	applied force (N)	aerodynamic drag force (N)	drivetrain drag force (N)	rolling resistance drag force (N)	total drag force (N)	net force (N)	net acceleration (m/s^2)	g force	tire slip?	time (sec.)	speed (mph)
1st gear	0	823.5	13,601	0.00	0.00	329.20	329.20	13,272	11.86	1.21	NO	0	0.00
1st gear	187.12	823.5	13,601	0.56	3.98	329.20	333.73	13,267	11.86	1.21	NO	0.1	2.65
1st gear	374.18	823.5	13,601	2.23	7.96	329.20	339.38	13,261	11.86	1.21	NO	0.2	5.31
1st gear	561.17	823.5	13,601	5.01	11.94	329.20	346.14	13,255	11.85	1.21	NO	0.3	7.96
1st gear	748.05	823.5	13,601	8.90	15.92	329.20	354.01	13,247	11.84	1.21	NO	0.4	10.61
1st gear	934.83	823.5	13,601	13.90	19.89	329.20	362.98	13,238	11.83	1.21	NO	0.5	13.26
1st gear	1,121.47	823.5	13,601	20.00	23.86	329.20	373.06	13,228	11.83	1.21	NO	0.6	15.91
1st gear	1,307.98	823.5	13,601	27.21	27.83	329.20	384.23	13,217	11.82	1.20	NO	0.7	18.55
1st gear	1,494.33	823.5	13,601	35.51	31.80	329.20	396.50	13,204	11.80	1.20	NO	0.8	21.20
1st gear	1,680.50	823.5	13,601	44.91	35.76	329.20	409.86	13,191	11.79	1.20	NO	0.9	23.84
1st gear	1,866.49	823.5	13,601	55.40	39.71	329.20	424.31	13,176	11.78	1.20	NO	1	26.48
1st gear	2,052.27	823.5	13,601	66.98	43.67	329.20	439.84	13,161	11.77	1.20	NO	1.1	29.11
1st gear	2,237.84	823.5	13,601	79.64	47.61	329.20	456.45	13,144	11.75	1.20	NO	1.2	31.74
1st gear	2,423.17	823.5	13,601	93.38	51.56	329.20	474.13	13,127	11.74	1.20	NO	1.3	34.37
1st gear	2,608.25	823.5	13,601	108.19	55.50	329.20	492.88	13,108	11.72	1.19	NO	1.4	37.00
1st gear	2,793.06	823.5	13,601	124.07	59.43	329.20	512.69	13,088	11.70	1.19	NO	1.5	39.62
1st gear	2,977.60	823.5	13,601	141.00	63.35	329.20	533.55	13,067	11.68	1.19	NO	1.6	42.24
1st gear	3,161.84	823.5	13,601	158.99	67.28	329.20	555.46	13,045	11.66	1.19	NO	1.7	44.85
1st gear	3,345.78	823.5	13,601	178.03	71.19	329.20	578.41	13,022	11.64	1.19	NO	1.8	47.46
1st gear	3,529.39	823.5	13,601	198.10	75.10	329.20	602.39	12,998	11.62	1.18	NO	1.9	50.06
1st gear	3,712.66	823.5	13,601	219.21	78.99	329.20	627.40	12,973	11.60	1.18	NO	2	52.66
1st gear	3,895.58	823.5	13,601	241.34	82.89	329.20	653.43	12,947	11.57	1.18	NO	2.1	55.26
1st gear	4,078.13	823.5	13,601	264.49	86.77	329.20	680.46	12,920	11.55	1.18	NO	2.2	57.85

5 Racepak Data Acquisition

The data acquisition package from Racepak, model V300, was used on the vehicle to be able to log many parameters for fine tuning of the vehicle and analysis. Data acquisition packages such as these are typically used on petrol-fuelled drag cars, but it was compatible with the electric drivetrain of this car and was able to log all of the necessary parameters. Below in Figure 3 is a screen capture of speed vs time from one of the two record runs. The record runs were within 0.01 seconds of each other.

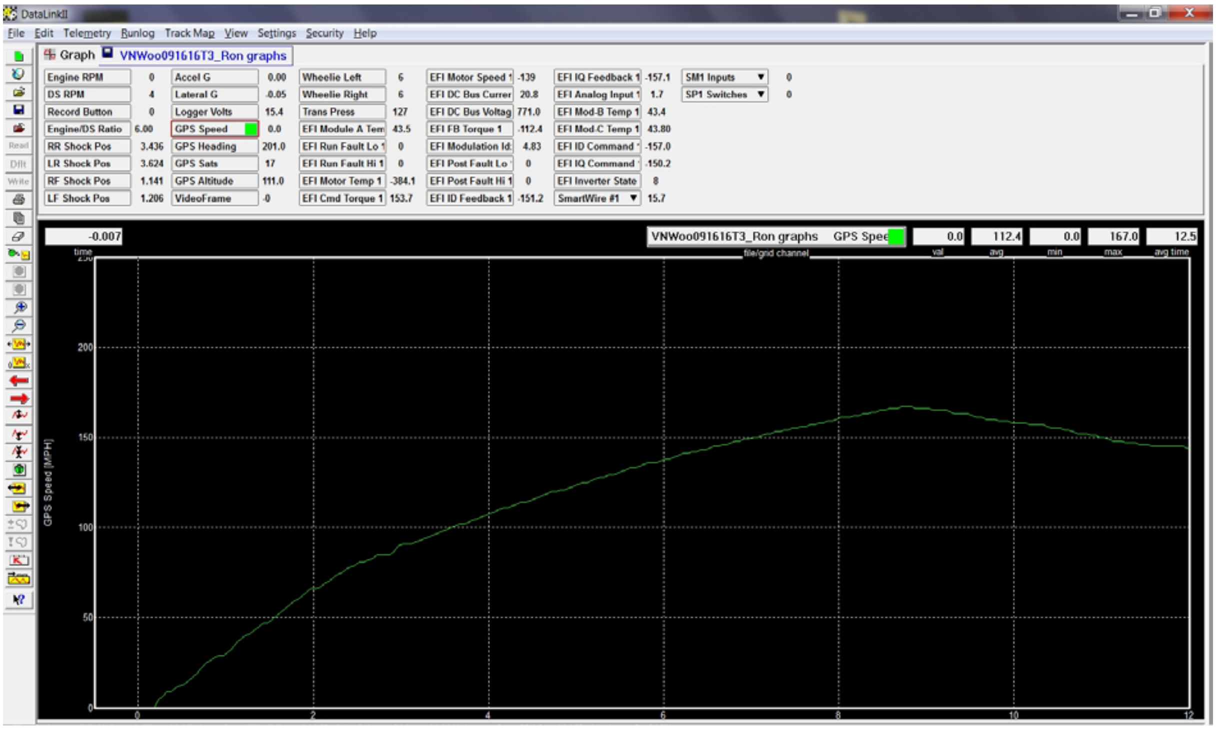

Figure 3: Racepak Data Acquisition Speed vs Time

An overlay of the plot of the calculated speed vs time from the drag race simulator and the actual speed vs time from the Racepak data acquisition is seen below in Figure 4.

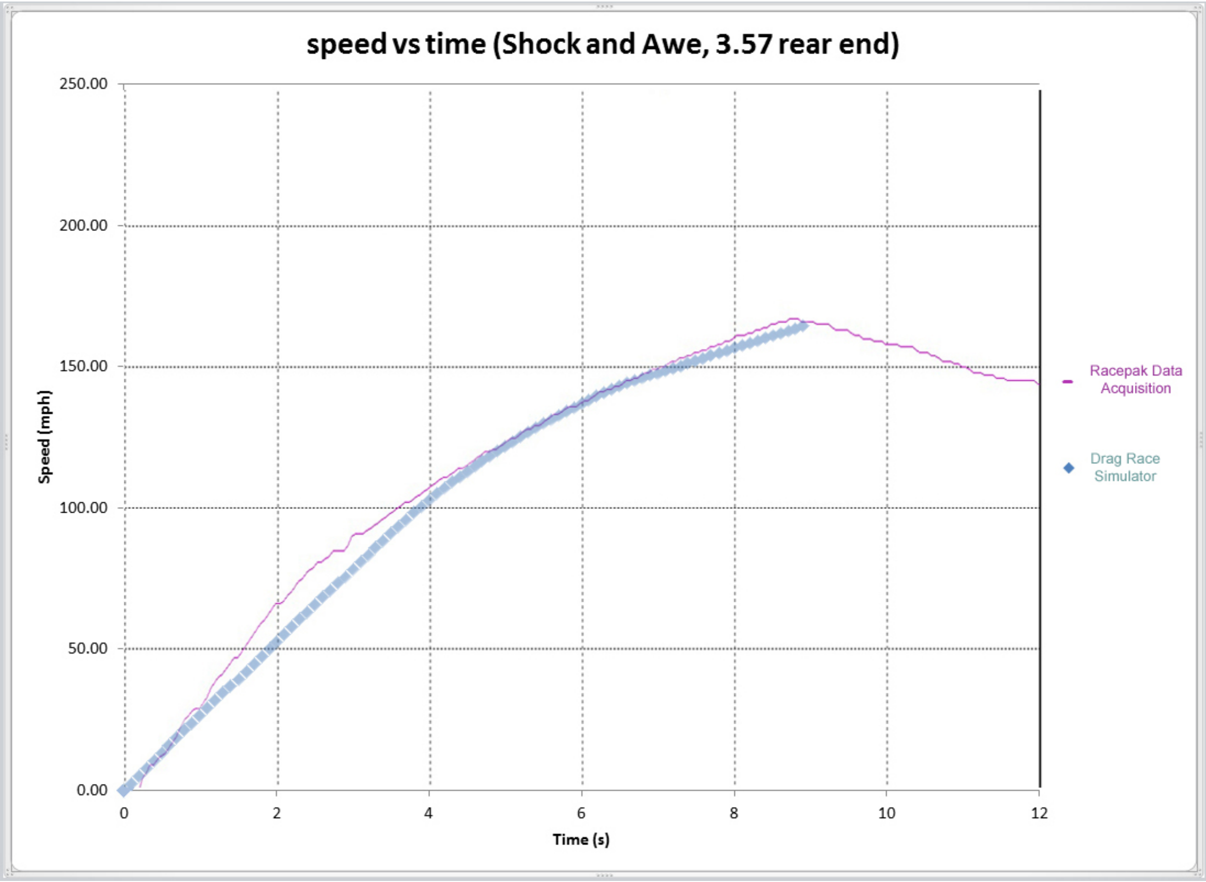

Figure 4: Overlay of Speed vs Time from Drag Racing Simulator and Racepak Data Acquisition

6 Conclusion

As seen above in Table 1 and Table 2, the predicted quarter mile elapsed time was 8.9 seconds at 164.35 mph. The actual world record run for a "door slammer" by Shock and Awe was 8.328 seconds elapsed time at a speed of 166.29 mph.[2] That is a 6.8% margin of error on the quarter mile elapsed time and 1.17% margin of error on the vehicle speed. Although the margin of error is relatively small, due to the elapsed time of the car being quicker than the simulation, there are factors that need to be investigated further with more data and testing of the vehicle to determine the sources of error in the simulator. Even with the error that is observed, the drag race simulator can give a relatively good estimate of the performance of an electric vehicle in a drag race given that you have all of the necessary parameters that are required as inputs in the drag race simulator. The most difficult to obtain of the necessary values would likely be the motor torque curve if the vehicle is not using a standard motor and controller with published torque curve data. The drag race simulator could also be applied to an internal combustion engine powered vehicle if desired as long as all of the required input parameters are available.

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