FD807 Electric Vehicle Component Sizing vs. Vehicle Structural Weight Report

Research Report

Conducted by Ricardo
for The Aluminum Association
2009 - 10

Scope of Work

This report was generated at the request of the Aluminum Association. The purpose of this study is to evaluate the impact of vehicle structural weight reduction on Electric Vehicle powertrain component size for various operating range targets.

Ricardo used previous data from the vehicle weight reduction study on fuel economy for light duty vehicles [FB769] to modify the small car and SUV models for EV operation. The FTP75 cycle was used to size the initial electric powertrain to achieve a 40 and 80 miles range. Also reported in this report is the range based on the HWFET cycle and 45 / 70 mph steady state operation. The baseline EV performance [0-30 mph, 0-60 mph] were kept comparable to the initial conventional vehicle.

For each iteration, the electrical powertrain weight was computed and deducted from the original conventional powertrain. The vehicle structural weight was updated based the new powertrain mass and size based on the Aluminum Association's structural weight computation. The electrical powertrain was then re-sized iteratively to keep range constant at similar performance.

Content

This report consists of the following sections:

- Conventional powertrain mass estimates
- EV Modeling and Assumptions
- Small Car EV sizing results
  - Small Car design space evaluation
  - FTP and HWFET Results
- Small SUV EV sizing Results
  - Small SUV design space evaluation
  - FTP and HWFET Results
- Weight Iterations and further optimization
- Conclusion.

Conventional Powertrain Masses

The original conventional powertrain masses for the two vehicles were estimated in the table below. The new EV powertrain masses will be estimated and compared for both vehicles. They do not include the fuel tank and battery.

Small Car

	Mass	Unit
Engine	97.0	kg
Eng ancillaries	10.0	kg
Electrical	13.0	kg
Cooling	11.5	kg
Exhaust	20.0	kg
Transmission	71.0	kg
Total	222.5	kg

Small SUV

	Mass	Unit
Engine	165.0	kg
Eng ancillaries	16.0	kg
Electrical	18.0	kg
Cooling	21.0	kg
Exhaust	39.0	kg
Transmission	102.0	kg
Total	361.0	kg

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EV Modeling General Assumptions

The EV vehicle was modeled and performance was measured using the following assumptions:

- The base EV rolling resistance coefficient and aero coefficient were unchanged from the baseline conventional numbers
- The EV powertrain is simplified to only use 1 fixed final drive ratio
- The number reported in this report for battery capacity represent the total capacity as opposed to usable capacity unless noted otherwise
- The usable SOC range was limited to a 0.9 to 0.25 range
- No thermal system simulation was performed
- The battery sizing was solely based on the FTP75 cycle results
- The motor sizing was based on the FTP75, 0-60 mph acceleration and top speed
- No additional performance for sizing was used in the analysis
- No additional load were added to the battery other than the propulsion motor request
- Motor was assumed to be capable of sustaining acceleration performance and top speed within the simulated transient time

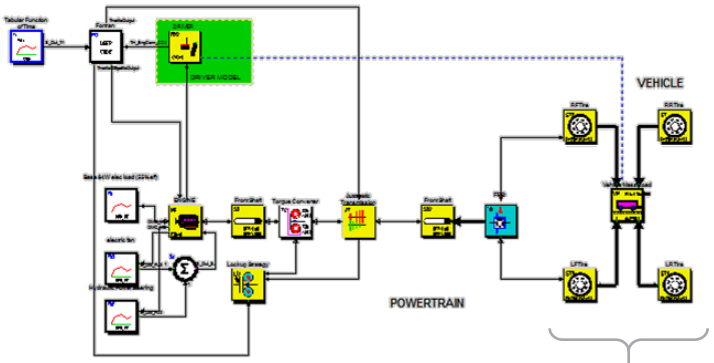
EV Models – Model Conversion from FB769

The following vehicle parameters were kept unchanged in the conversion from the Conventional Powertrain from the previous study to the new Electrical Powertrain. The EV powertrain was modeled using Ricardo EASY5 Powertrain Library.

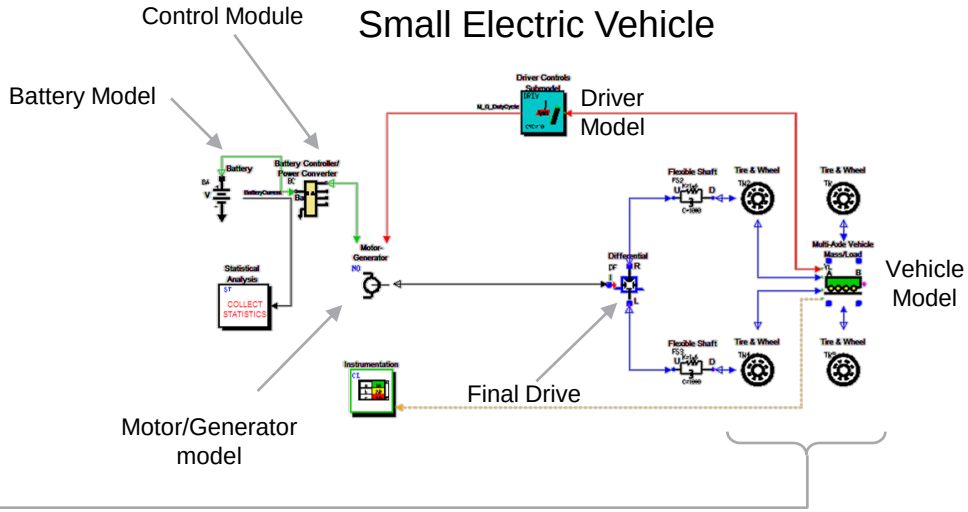
Note: the constant portion of the rolling resistance is dependant on vehicle mass and hence will vary as vehicle mass is updated.

		Vehicle	
	units	Small Car	Small SUV
Base Weight	kg	1304	1927
Wheelbase	m	2.466	2.708
Cd.A*	m²	0.7	1
Tire Rollign Radius	m	0.294	0.344
Cste Rolling Resistance	N.m	11.67	15.49
Rolling Resistance Speed Effect	N.s	0	0.292

Conventional Small Vehicle



Small Electric Vehicle



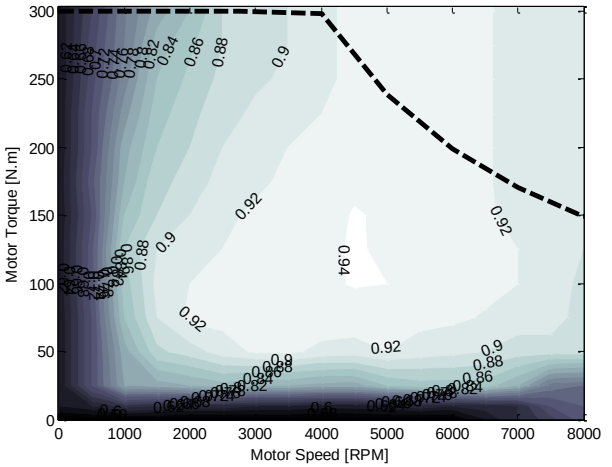
* Cd = aero coefficient, A = frontal area

Basic Modeling Inputs Description

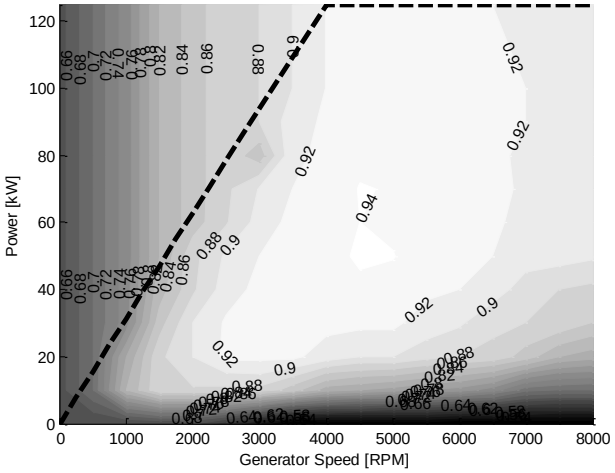
The electric powertrain is populated with the following data :

- Battery [Lithium Ion]
  - Open Circuit Voltage: 360 V
  - SOC range [usable]: 0.9 - 0.25
  - Usable energy to mass of pack: approx.115 W-h/kg
  - Usable energy to volume of pack: approx.155 W-h/L
  - Price for Total energy: $750/kWh as provided by the Aluminum Association
- Electric Motor / Generator
  - Performance and Efficiency scaled based on UQM 125 kW motor, 300 N.m machine
  - Motor and Generator Efficiency plotted on the right
  - Max Speed maintained at 8000 rpm
  - Power Density: approx. 3.05 kW/kg kept constant
- Motor Controller
  - Control Electric Motor based on driver vehicle speed demand
  - 95% Efficiency in Power Conversion
  - Regen-braking threshold set at 1000N braking, when throttle = 0
  - Mass approximated to 14 kg.
- Fixed Final Drive
  - Sized for both vehicles, 98% efficiency

Motor Characteristics



Generator Characteristics



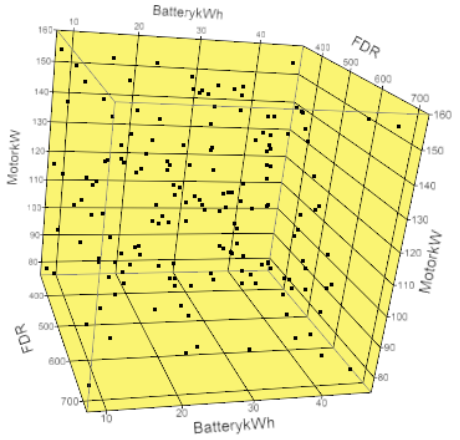
EV Models – Electrical Powertrain Modeling and Assumptions

The small car and SUV electric powertrain components [battery and motor size, final ratio] are sized in order to achieve the following vehicle performance:

- Ranges:
  - 40 miles
  - 80 miles
- Acceleration:
  - 0-60 mph: similar to baseline conventional vehicles [within 1-2s]
- Top Speed:
  - Around 90-110 mph [similar to published Volt, BMW Mini EV information]

As the vehicle weight will be modified, vehicle weight effect and its interactions with the rest of the electrical components is studied via Design of Experiments. The DoE design variables are:

- Battery size: 10 – 40 kWh [usable energy]
- Motor / Generator size [linear scaling of the torque axis in efficiency maps]: 80 – 150 kW
- Final Drive Ratio: 4:1 – 8:1
- Vehicle Weight Reduction: 0 – 700 kg
- Max Torque Speed range [40% to 70% of motor speed range]



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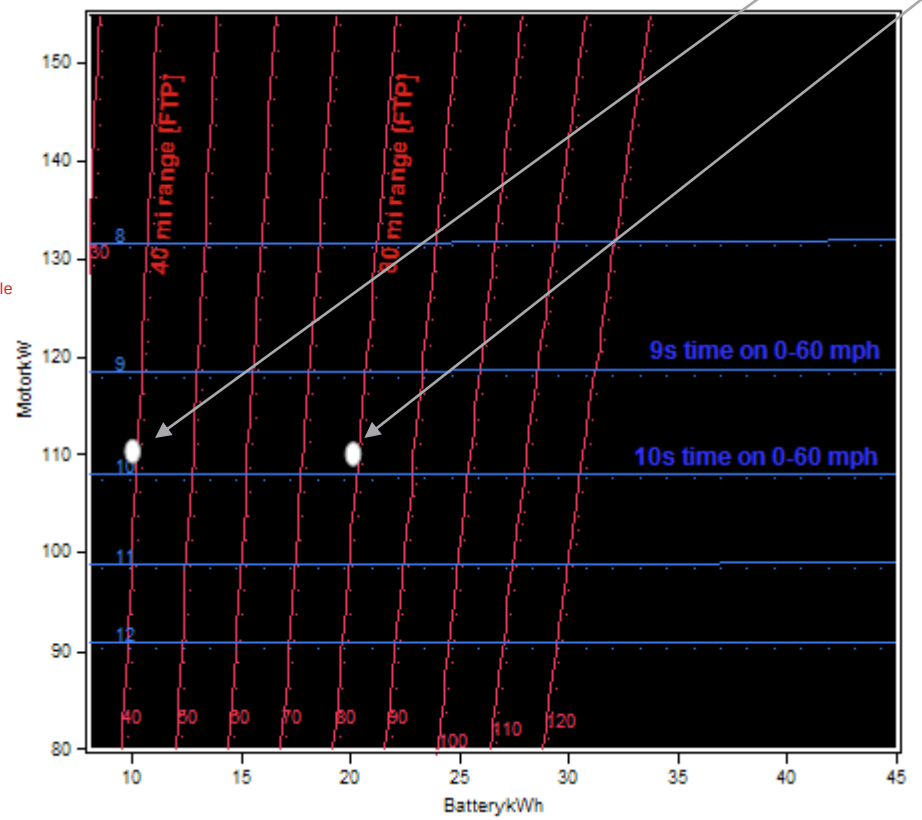
Small Car EV Base Model Design [40 & 80 miles range]

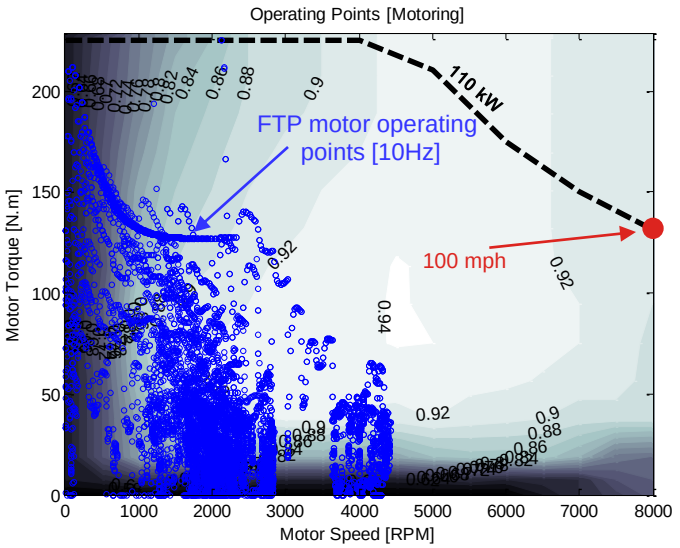
Mass Constant @ 1304 kg

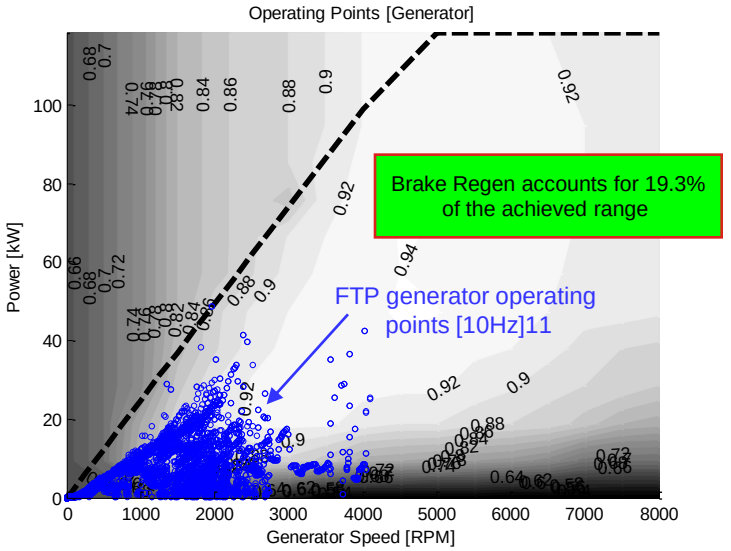
The base Mini EV set up is based on FTP results for range, acceleration performance and top speed [limit 100mph].

		40 mi	80 mi
Battery Size Usable / Total	kWh	9.5 / 14.6	18.7 / 28.7
Motor Size	kW	110.2	110.2
Final Drive		5.32:1	5.32:2
Vehicle Weight	kg	1304.7	1304.7
Rated Speed Factor	%	58%	58%

Conventional Vehicle
0-60 mph = 10.3s



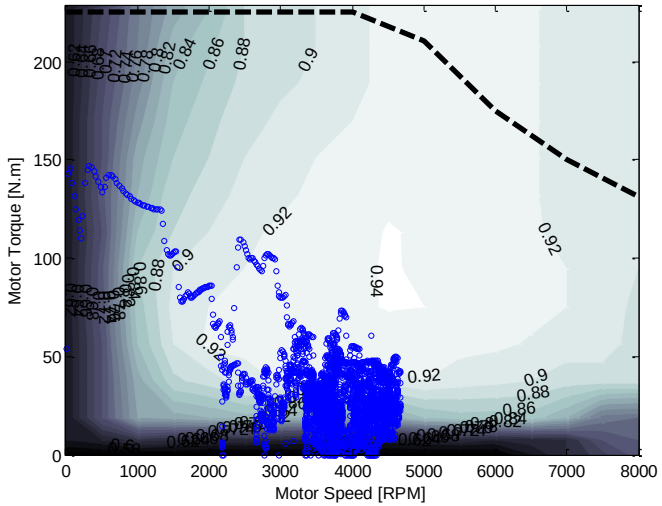


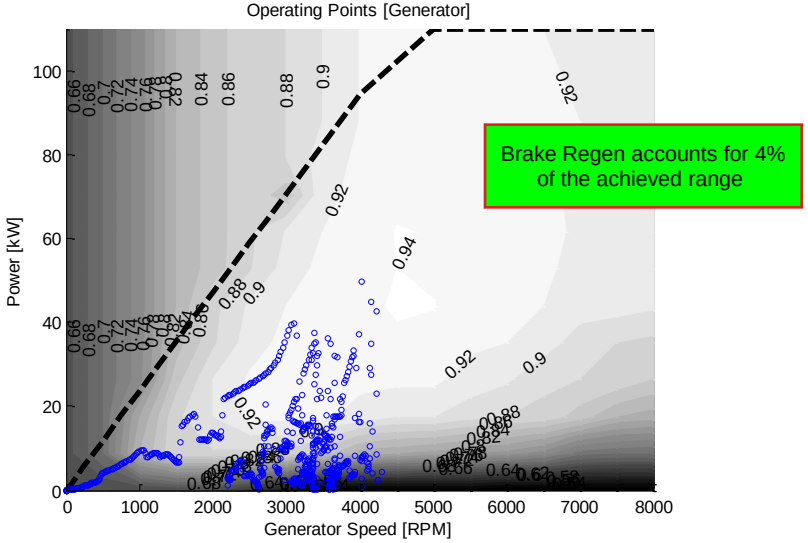


Small Car EV Base Model Operation

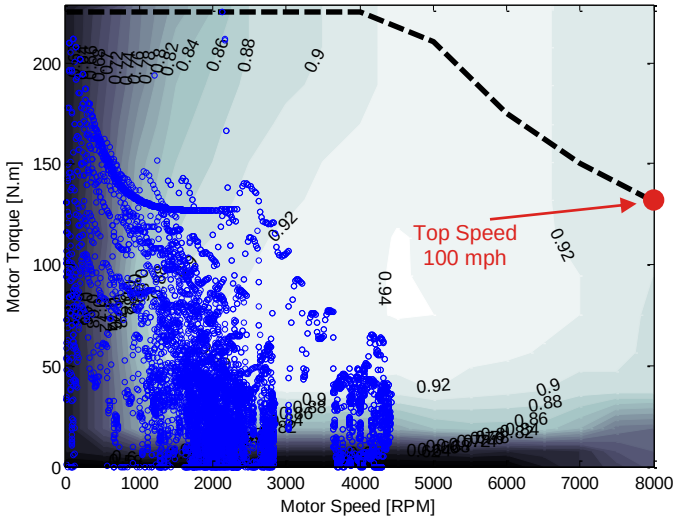
HWFET range is 39.4 miles with the 14.6 kWh [total] battery, and 77.5 mi with the 28.7 kWh [total] battery. Lower brake regen is available on the HWFET.

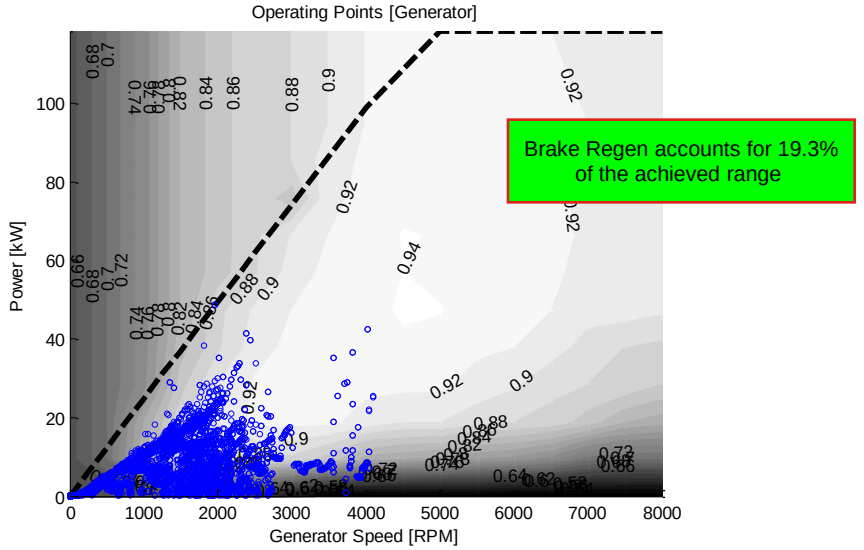
HWFET Operating Points





FTP and Top Speed Operating Points





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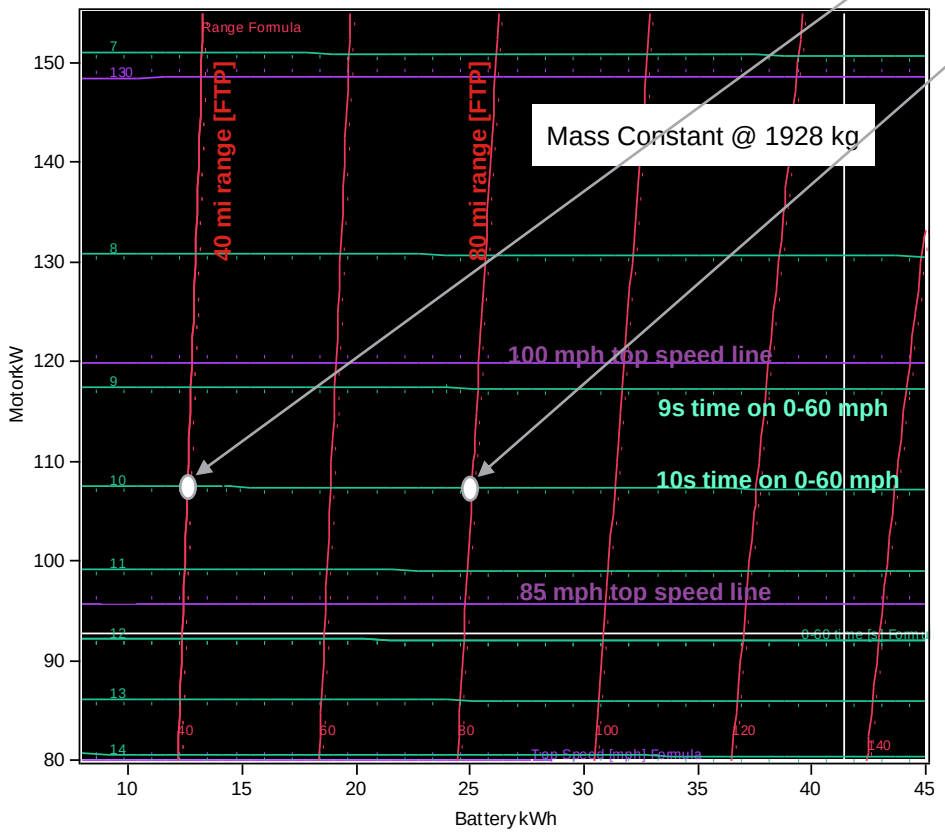
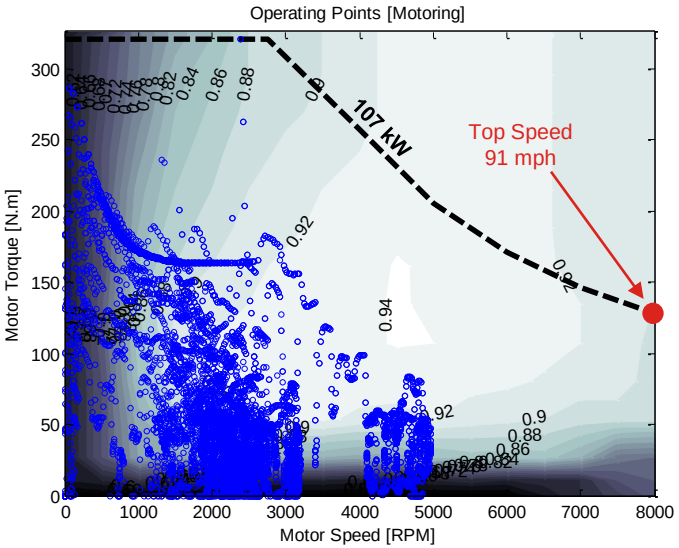
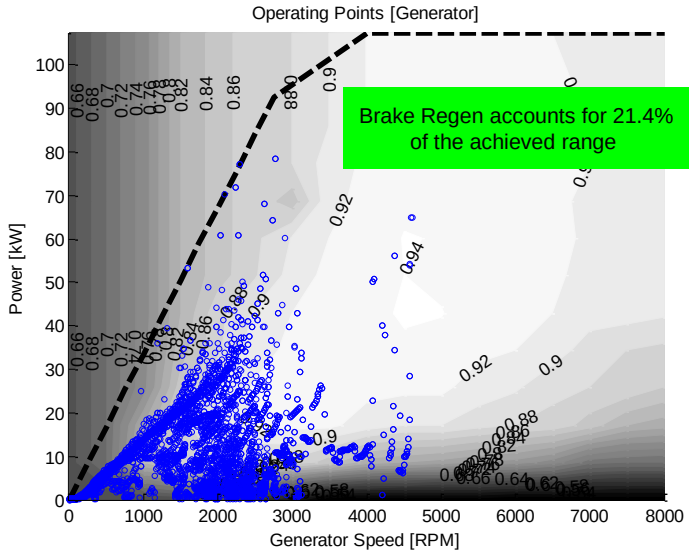
Small SUV EV Base Model Design [40 & 80 miles range]

The base small SUV EV set up is based on FTP results for range, acceleration performance and top speed [limit 90mph]. Higher FDR were needed to meet 0-60 mph acceleration [10s vs. 9.3s conventional].

		40 mi	80 mi
Battery Size Usable / Total	kWh	12.7 / 19.5	24.9 / 38.3
Motor Size	kW	107.3	107.3
Final Drive		7:1	7:1
Vehicle Weight	kg	1928	1928
Rated Speed Factor	%	40%	40%



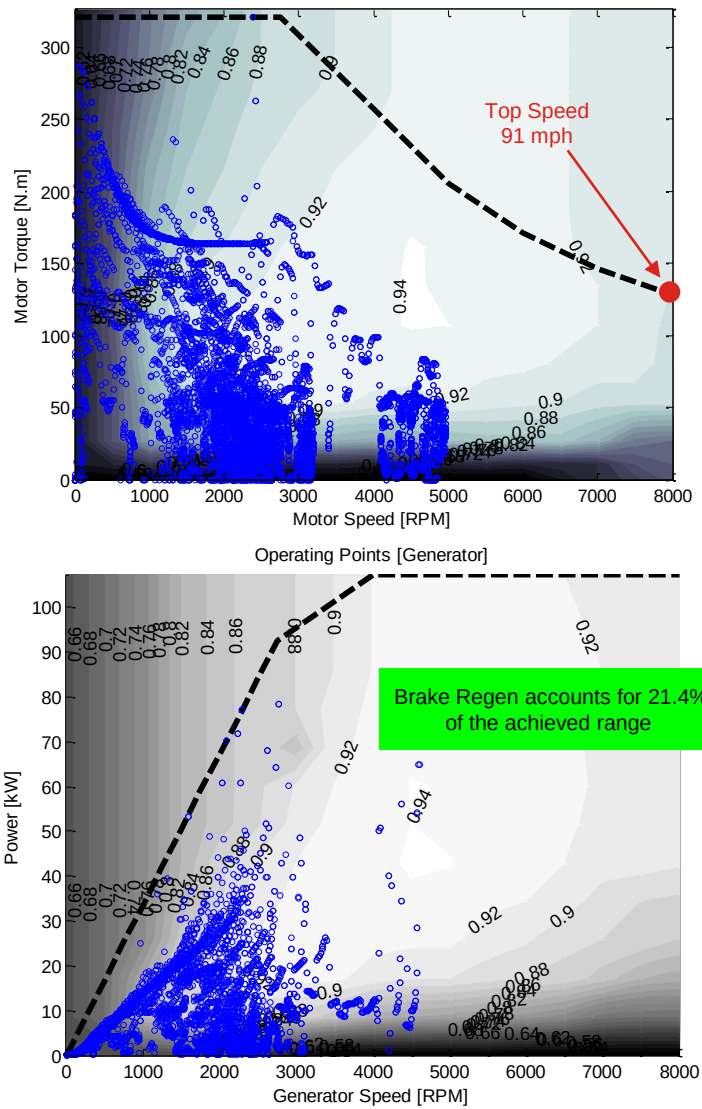




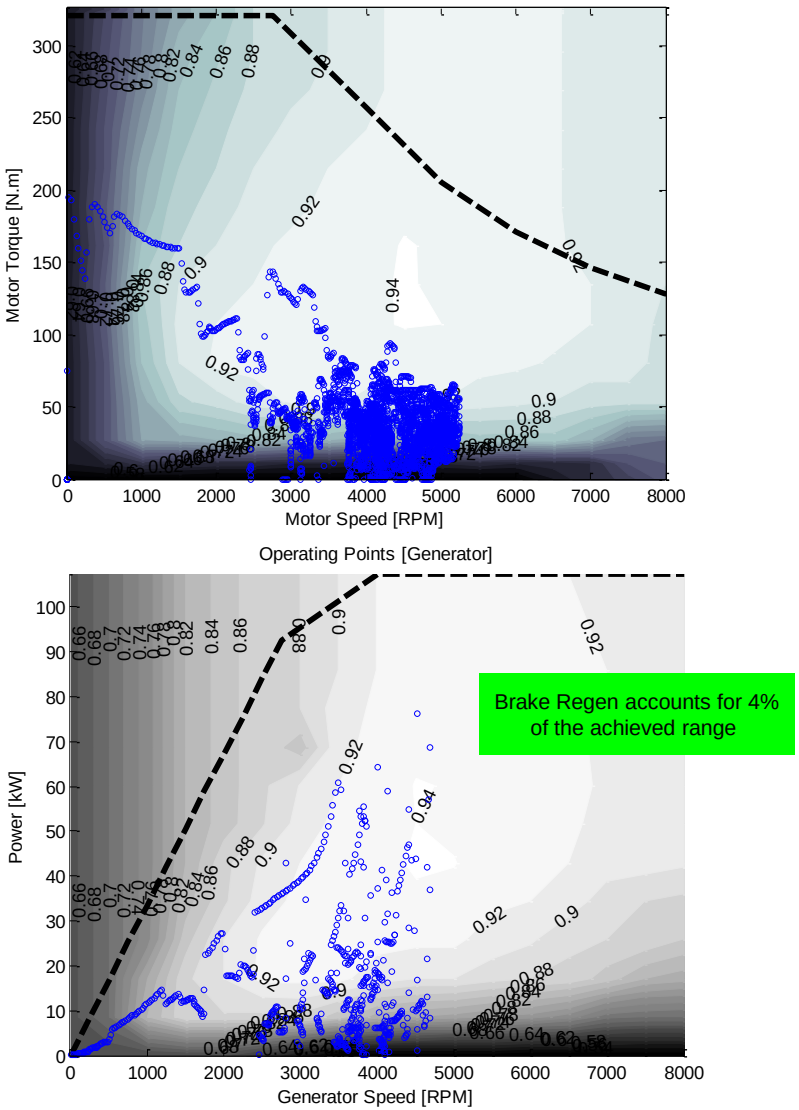
Small EV Base Model Operation

HWFET range is also 37.5 miles with the 19.5 kWh [total] battery, and 73.5 mi with the 38.3 kWh [total] battery.

FTP Operating Points



HWFET Operating Points



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Weight Iterations Cases

The Aluminum Association provided the new vehicle weights for 4 architecture cases. The new weights were plugged in the model and the battery was resized in order to keep the EVs' range to 40 and 80 miles. Two iterations were performed in order to match the EV powertrain mass to the new vehicle mass. Battery rating and cost difference with the initial conventional vehicle weight is computed. The EV powertrain was also re-sized to further optimize for efficiency.

Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure

- Use Base Vehicle Steel Structure
- Partially removed the conventional powertrain weight to represent a Extended EV / Series Hybrid *
- Added EV Powertrain Weight

Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure

- Use Aluminum Structure
- Partially removed the powertrain weight to represent a Extended EV / Series Hybrid *
- Added EV Powertrain Weight

Case 3: Weight Represent a Full EV Configuration with Steel Structure

- Use Steel Structure
- Removed the entire baseline conventional powertrain weight
- Added EV Powertrain Weight

Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

- Use Aluminum Structure
- Removed the entire base baseline conventional powertrain weight
- Added EV Powertrain Weight

* Note: All performance runs are in full EV mode only.

Un-optimized Weight Iterations Results – Small Car

Two iterations are necessary to match the vehicle weight to the EV powertrain weight. The Aluminum structure provided the opportunity to reduce battery cost by about $5,600. Further optimization is necessary in order to match the motor rating to the new vehicle weight with a potential secondary effect on downsizing the battery.

			40 MILE RANGE				80 MILE RANGE			
	Small EV	Units	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
	Base Weight	kg	1304	1142	684.6	539.2	1304	1142	684.6	539.2
	Subtract Conv. Powertrain	kg	223	223	Fully Substracted	Fully Substracted	223	223	Fully Substracted	Fully Substracted
	Base EV/Ext. EV Weight	kg	1082	920	685	539	1082	920	685	539
ITERATION 1	Battery Size [Total]	kWh	12.9	11.8	10.5	9.4	25.8	23.7	20.6	18.8
ITERATION 1	Motor Size	kW	110	110	110	110	110	110	110	110
ITERATION 1	Battery Weight	kg	73	67	59	53	146	134	117	106
ITERATION 1	Motor + Controller Weight	kg	50	50	50	50	50	50	50	50
ITERATION 1	E-Powertrain Weight	kg	123	117	109	103	196	184	167	156
ITERATION 1	Weight Iteration 1	kg	1205	1037	794	642	1278	1103	851	695
ITERATION 2	Battery Size [Total]	kWh	13.8	12.6	11.1	10.2	28.3	26.0	22.8	20.8
ITERATION 2	Motor Size	kW	110	110	110	110	110	110	110	110
ITERATION 2	Battery Weight	kg	78	71	63	57	160	147	129	117
ITERATION 2	Motor + Controller Weight	kg	50	50	50	50	50	50	50	50
ITERATION 2	E-Powertrain Weight	kg	128	121	113	107	210	197	179	167
ITERATION 2	Weight Iteration 2	kg	1210	1041	797	647	1292	1117	863	707
Un-optimized	Battery Cost Gain	$	$0	$923	$2,077	$2,769	$0	$1,731	$4,154	$5,654

Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

Un-optimized Weight Iterations Results – Small SUV

Two iterations are necessary to match the vehicle weight to the EV powertrain weight. The Aluminum structure provided the opportunity to reduce battery cost by about $6,500. Further optimization is necessary in order to match the motor rating to the new vehicle weight with a potential secondary effect on downsizing the battery.

			40 MILE RANGE				80 MILE RANGE			
	Small SUV EV	Units	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
	Base Weight	kg	1928	1689	1014	798	1928	1689	1014	798
	Subtract Powertrain	kg	361	361	Fully Substracted	Fully Substracted	361	361	Fully Substracted	Fully Substracted
	Base EV/Ext. EV Weight	kg	1567	1328	1014	798	1567	1328	1014	798
ITERATION 1	Battery Size [Total]	kWh	17.2	16.0	14.5	13.4	34.3	32.0	28.8	26.6
ITERATION 1	Motor Size	kW	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
ITERATION 1	Battery Weight	kg	97	90	82	76	194	181	163	150
ITERATION 1	Motor + Controller Weight	kg	49	49	49	49	49	49	49	49
ITERATION 1	E-Powertrain Weight	kg	147	140	131	125	243	230	212	200
ITERATION 1	Weight Iteration 1	kg	1714	1468	1145	923	1810	1558	1226	998
ITERATION 2	Battery Size [Total]	kWh	18.2	16.8	15.1	14.0	37.2	34.3	30.8	28.6
ITERATION 2	Motor Size	kW	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
ITERATION 2	Battery Weight	kg	103	95	85	79	210	194	174	162
ITERATION 2	Motor + Controller Weight	kg	49	49	49	49	49	49	49	49
ITERATION 2	E-Powertrain Weight	kg	152	144	134	128	260	243	223	211
ITERATION 2	Weight Iteration 2	kg	1719	1472	1149	927	1827	1571	1237	1009
Un-optimized	Battery Cost Gain	$	$0	$1,038	$2,308	$3,115	$0	$2,192	$4,846	$6,462

Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
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Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

Powertrain Optimization

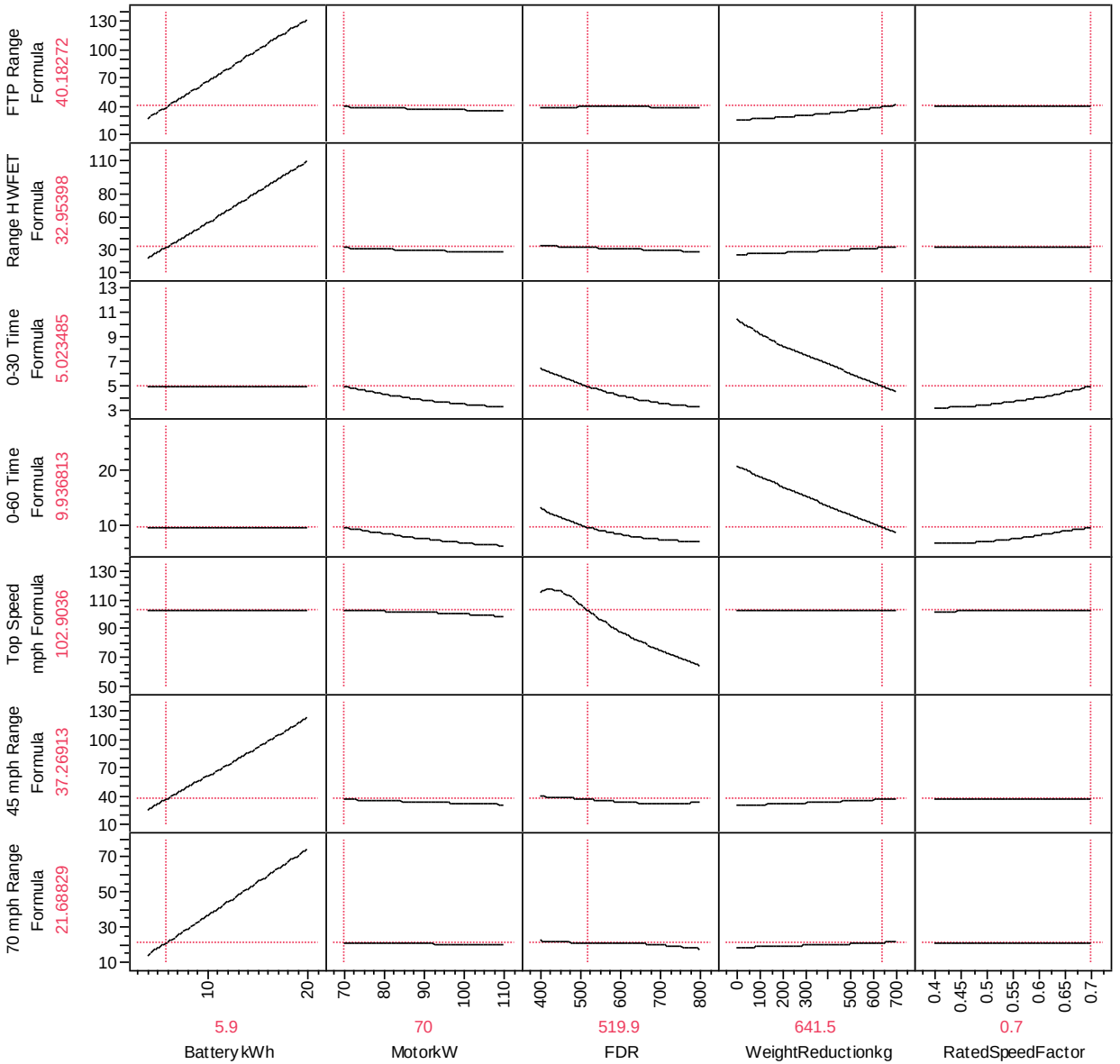
Response Surface Models [RSM] are created for:

- FTP Range [design target]
- HWFET Range
- Steady State at 45 and 70 mph
- Acceleration: 0-30 & 0-60 mph
- Top Speed

The RSM R^2 are around 0.99, hence the models are accurate to optimize for range while constraining for acceleration and top speed. Once the design variables are set using the RSM, the model is run to check for the performance.

The table on the right shows the prediction profile for the small car, Case 4 [40 mi range].

All the RSM plots for each cases are in Appendix A.



Small Car Results

			40 MILE RANGE				80 MILE RANGE			
	Small EV	Units	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
	Base Weight	kg	1304	1142	684.6	539.2	1304	1142	684.6	539.2
	Subtract Conv. Powertrain	kg	223	223	Fully Substracted	Fully Substracted	223	223	Fully Substracted	Fully Substracted
	Base EV/Ext. EV Weight	kg	1082	920	685	539	1082	920	685	539
ITERATION 1	Battery Size [Total]	kWh	12.9	11.8	10.5	9.4	25.8	23.7	20.6	18.8
ITERATION 1	Motor Size	kW	110	110	110	110	110	110	110	110
ITERATION 1	Battery Weight	kg	73	67	59	53	146	134	117	106
ITERATION 1	Motor + Controller Weight	kg	50	50	50	50	50	50	50	50
ITERATION 1	E-Powertrain Weight	kg	123	117	109	103	196	184	167	156
ITERATION 1	Weight Iteration 1	kg	1205	1037	794	642	1278	1103	851	695
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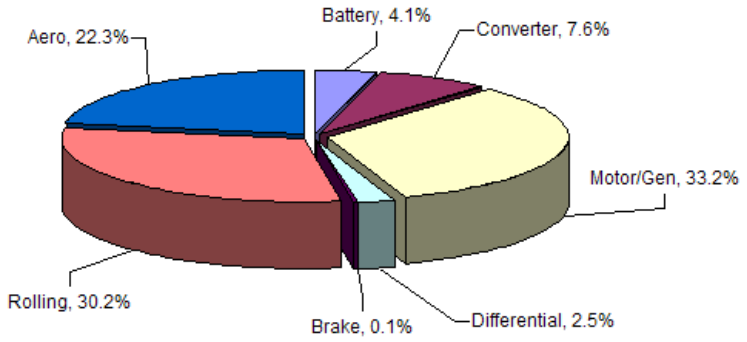
ITERATION 2	Motor Size	kW	110	110	110	110	110	110	110	110
ITERATION 2	Battery Weight	kg	78	71	63	57	160	147	129	117
ITERATION 2	Motor + Controller Weight	kg	50	50	50	50	50	50	50	50
ITERATION 2	E-Powertrain Weight	kg	128	121	113	107	210	197	179	167
ITERATION 2	Weight Iteration 2	kg	1210	1041	797	647	1292	1117	863	707
Un-optimized	Battery Cost Gain	$	$0	$923	$2,077	$2,769	$0	$1,731	$4,154	$5,654
OPTIMIZATION	Motor Size	kW	101.0	88.0	73.0	70.0	107.0	93.0	80.0	70.0
OPTIMIZATION	FDR		5.37	5.34	5.37	5.20	5.32	5.37	5.34	5.31
OPTIMIZATION	Rated Speed		0.58	0.58	0.61	0.70	0.58	0.58	0.62	0.58
OPTIMIZATION	Battery Size [Total]	kWh	13.5	12.2	10.3	9.1	28.2	25.4	21.5	19.1
OPTIMIZATION	Battery Weight	kg	77	69	58	51	159	17	121	108
OPTIMIZATION	Motor + Controller Weight	kg	47	43	38	37	49	44	40	37
OPTIMIZATION	Optimized Weight	kg	1,205	1,031	781	627	1,290	980	846	684
OPTIMIZATION	Battery Cost Gain	$	$0	$1,038	$2,423	$3,346	$0	$2,077	$5,008	$6,808
OPTIMIZATION	HWFET Range	mi	37	36	35	33	76	74	69	67
OPTIMIZATION	45 mph range	mi	41	41	39	37	82	81	77	74
OPTIMIZATION	70 mph range	mi	28	26	24	21	57	54	49	46
OPTIMIZATION	0-30 mph Accel Time	s	4.8	4.9	4.8	5.0	4.9	4.9	4.8	4.9
OPTIMIZATION	0.60 mph Accel Time	s	9.9	10.0	10.0	9.9	10.0	10.0	10.0	10.0
OPTIMIZATION	Top Speed	mph	100	100	100	100	101	100	100	100

See Appendix A for plots

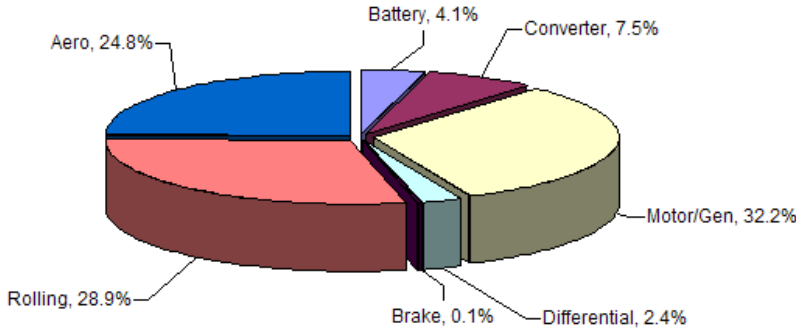
Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

Small Car Results – Energy Usage

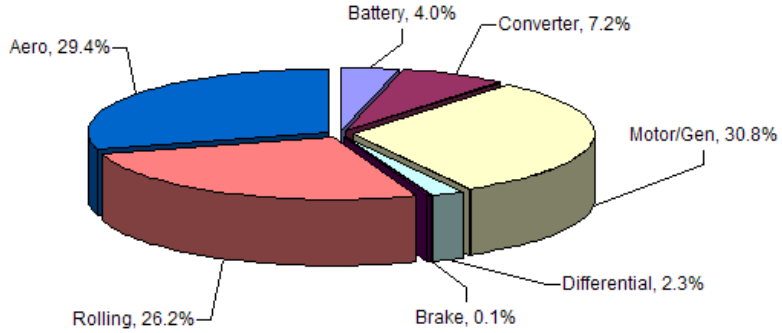
Case 1: 1205 kg
[Regen = 20.9%]



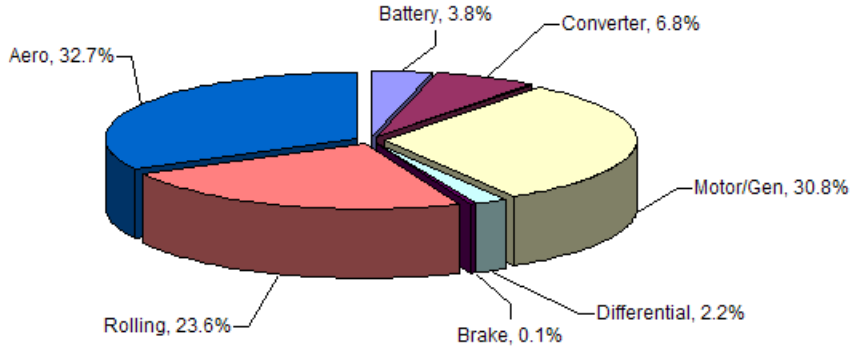
Case 2: 1031 kg
[Regen = 20%]



Case 3: 781 kg
[Regen = 18.1%]

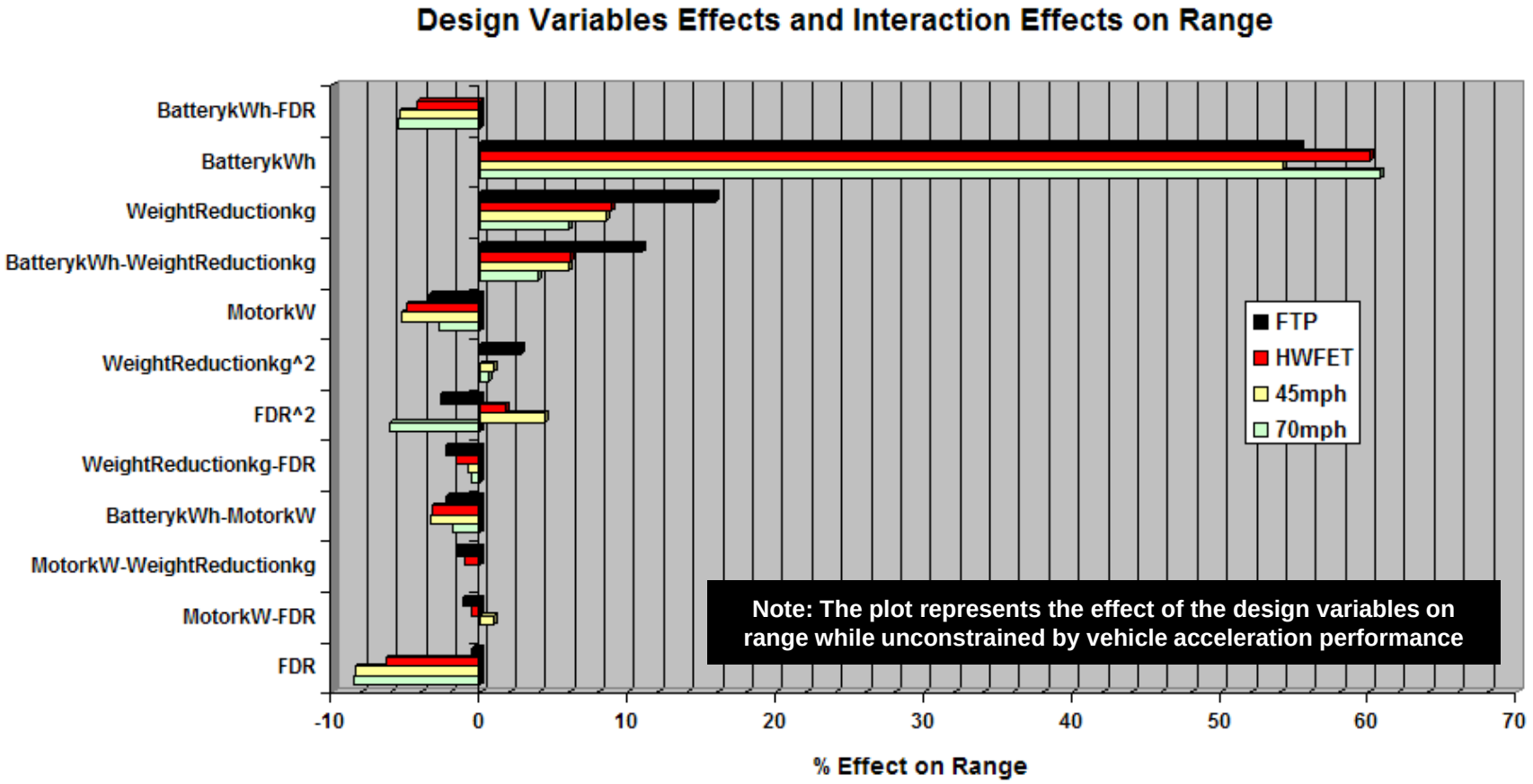


Case 4: 627 kg
[Regen = 15.6%]



Small Car Results – Pareto Plots [Range]

Based on a quadratic regression analysis order, the pareto plots show that the main effects for vehicle range improvement are driven by the battery size, vehicle weight reduction and the interaction between battery size and weight reduction. The FTP range is also more sensitive to the vehicle weight than the other cycle. FDR trends are negative but acceleration time would be inversely affected – multi-ratio transmission would enable optimization of the range on a wider range of operation.



Small SUV Results

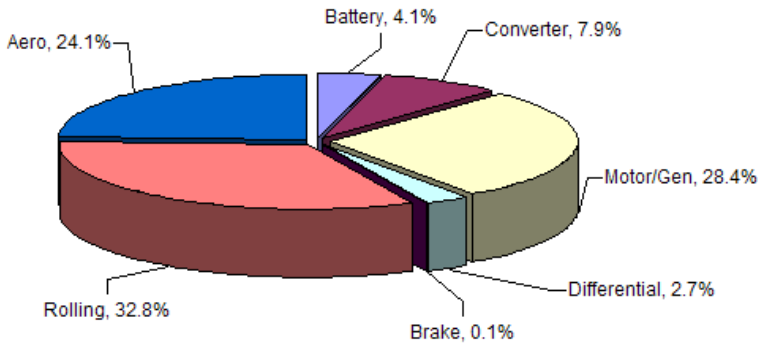
			40 MILE RANGE				80 MILE RANGE			
	Small SUV EV	Units	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
	Base Weight	kg	1928	1689	1014	798	1928	1689	1014	798
	Subtract Powertrain	kg	361	361	Fully Substracted	Fully Substracted	361	361	Fully Substracted	Fully Substracted
	Base EV/Ext. EV Weight	kg	1567	1328	1014	798	1567	1328	1014	798
ITERATION 1	Battery Size [Total]	kWh	17.2	16.0	14.5	13.4	34.3	32.0	28.8	26.6
ITERATION 1	Motor Size	kW	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
ITERATION 1	Battery Weight	kg	97	90	82	76	194	181	163	150
ITERATION 1	Motor + Controller Weight	kg	49	49	49	49	49	49	49	49
ITERATION 1	E-Powertrain Weight	kg	147	140	131	125	243	230	212	200
ITERATION 1	Weight Iteration 1	kg	1714	1468	1145	923	1810	1558	1226	998
ITERATION 2	Battery Size [Total]	kWh	18.2	16.8	15.1	14.0	37.2	34.3	30.8	28.6
ITERATION 2	Motor Size	kW	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
ITERATION 2	Battery Weight	kg	103	95	85	79	210	194	174	162
ITERATION 2	Motor + Controller Weight	kg	49	49	49	49	49	49	49	49
ITERATION 2	E-Powertrain Weight	kg	152	144	134	128	260	243	223	211
ITERATION 2	Weight Iteration 2	kg	1719	1472	1149	927	1827	1571	1237	1009
Un-optimized	Battery Cost Gain	$	$0	$1,038	$2,308	$3,115	$0	$2,192	$4,846	$6,462
OPTIMIZATION	Motor Size	kW	96.0	84.0	71.0	70.0	100.0	89.0	74.0	70.0
OPTIMIZATION	FDR		7.00	7.00	6.46	6.00	7.00	7.00	6.70	6.66
OPTIMIZATION	Rated Speed		0.40	0.40	0.40	0.47	0.40	0.40	0.40	0.46
OPTIMIZATION	Battery Size [Total]	kWh	17.4	15.9	14.2	13.0	36.9	33.5	29.2	26.6
OPTIMIZATION	Battery Weight	kg	98	90	80	73	209	190	165	150
OPTIMIZATION	Motor + Controller Weight	kg	45	42	37	37	47	43	38	37
OPTIMIZATION	Optimized Weight	kg	1,711	1,460	1,132	909	1,822	1,561	1,218	986
OPTIMIZATION	Battery Cost Gain	$	$0	$1,096	$2,377	$3,300	$0	$2,527	$5,758	$7,742
OPTIMIZATION	HWFET Range	mi	35	34	33	32	73	70	66	63
OPTIMIZATION	45 mph range	mi	40	39	39	37	82	79	77	73
OPTIMIZATION	70 mph range	mi	24	23	22	21	51	48	44	41
OPTIMIZATION	0-30 mph Accel Time	s	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.4
OPTIMIZATION	0.60 mph Accel Time	s	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.7
OPTIMIZATION	Top Speed	mph	91	91	97	101	90	91	95	95

See Appendix A for plots

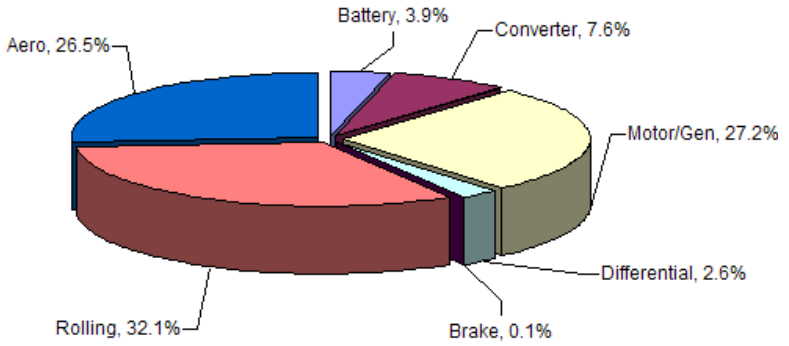
Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

Small SUV Results – Energy Usage

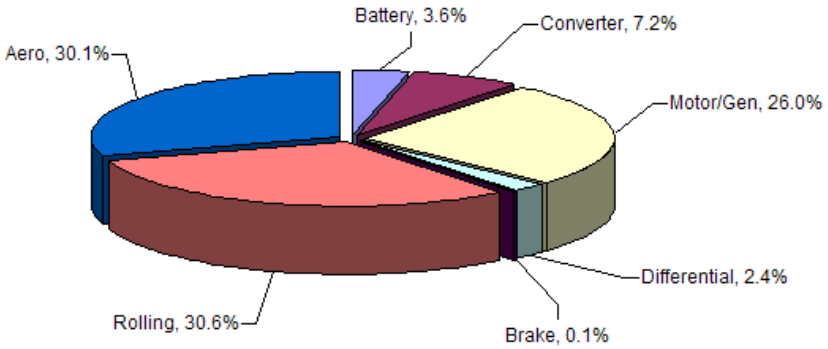
Case 1: 1719 kg
[Regen = 22.7%]



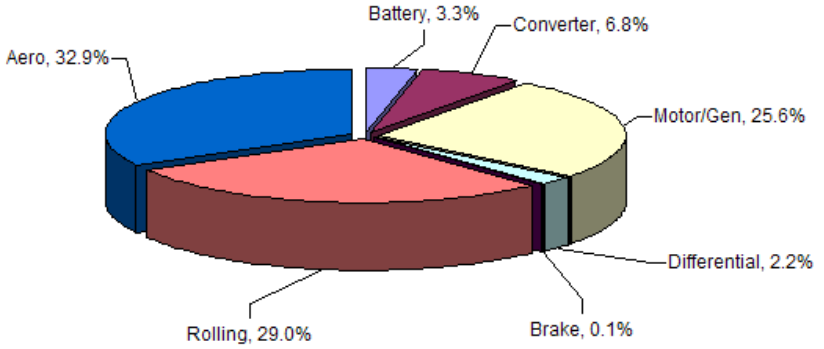
Case 2: 1460 kg
[Regen = 21.4%]



Case 3: 1132 kg
[Regen = 18.3%]



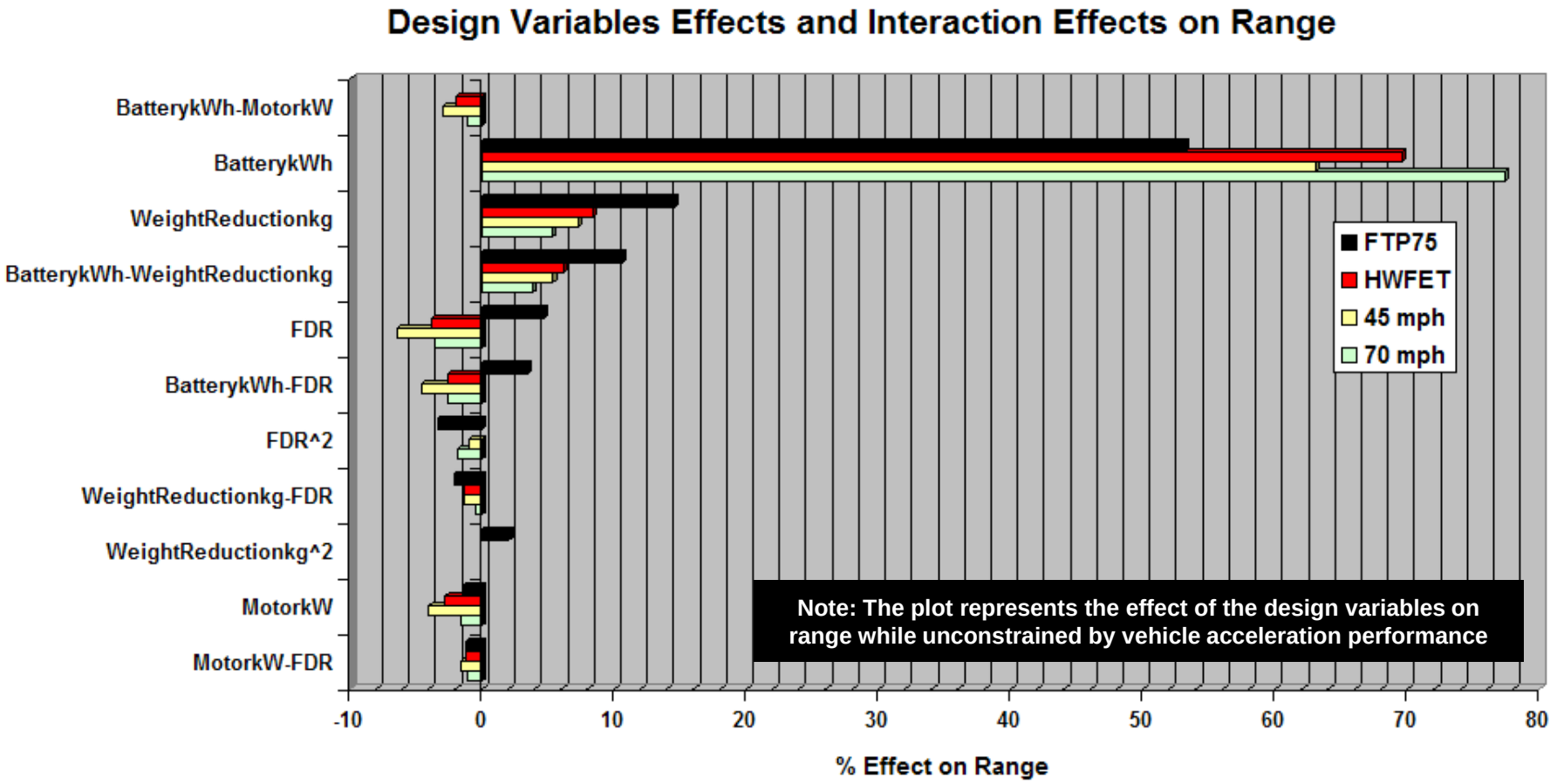
Case 4: 927 kg
[Regen = 15.6%]



Case 1: Weight Represent a Series Hybrid / Extended EV Configuration with Steel Structure
Case 2: Weight Represent a Series Hybrid / Extended EV Configuration with Aluminum Structure
Case 3: Weight Represent a Full EV Configuration with Steel Structure
Case 4: Weight Represent a Full EV Configuration with Aluminum Structure

Small SUV Results – Pareto Plots [Range]

Based on a quadratic regression analysis order, the pareto plots show that the main variables for vehicle range improvement are the battery size, vehicle weight reduction and the interaction between battery size and weight reduction. The FDR effect on the FTP is different than for the other cycles – hence an optimized system for a wide range of operation would need more than 1 fixed ratio. The FTP sensitivity to battery size is lower than the other cycles thanks to higher braking regeneration.

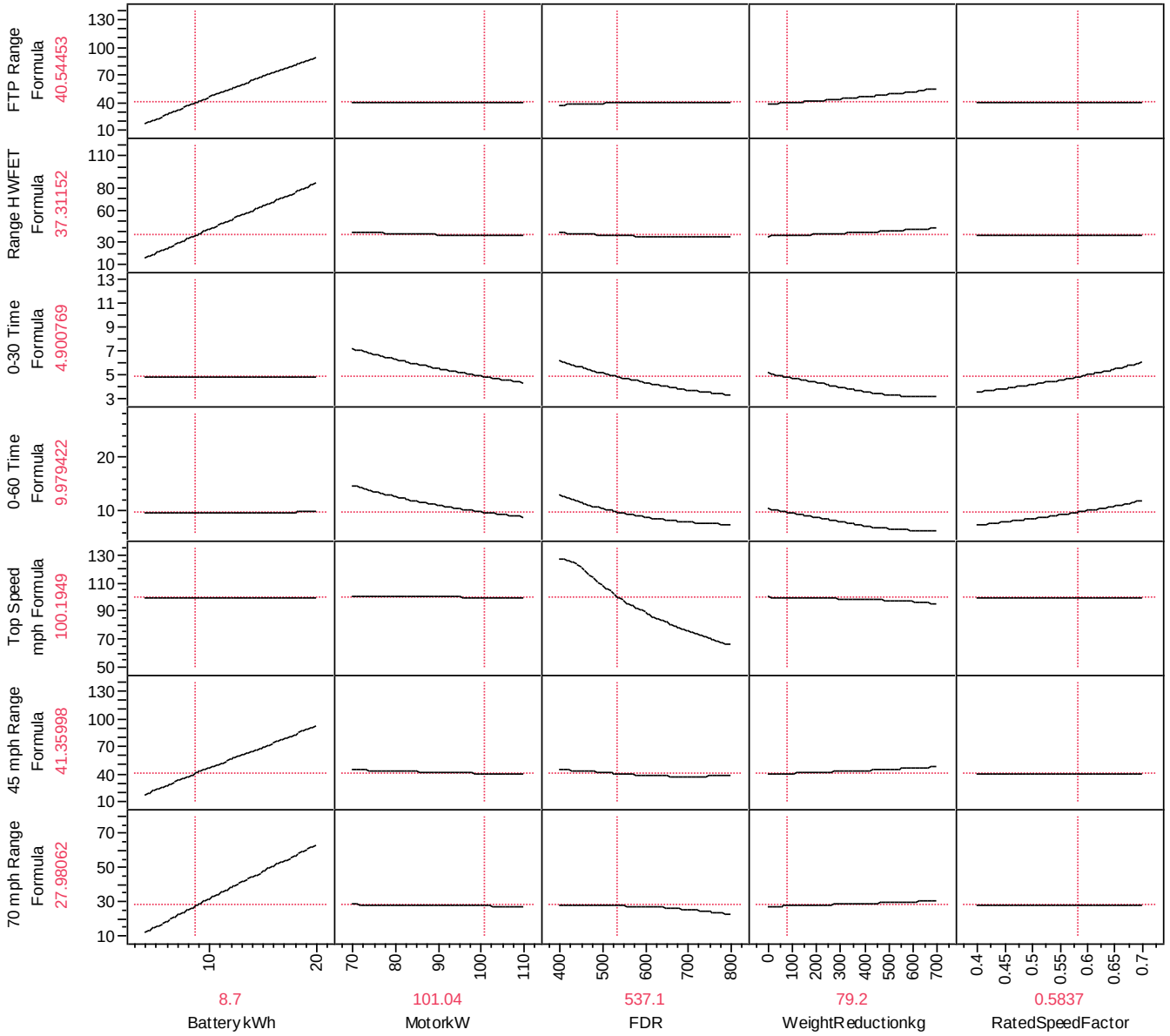


Content

- Conventional powertrain mass estimates
- EV Modeling and Assumptions
- Small Car EV sizing results
  - Small Car design space evaluation
  - FTP and HWFET Results
- Small SUV EV sizing Results
  - Small SUV design space evaluation
  - FTP and HWFET Results
- Weight Iterations and further optimization
- Conclusion.

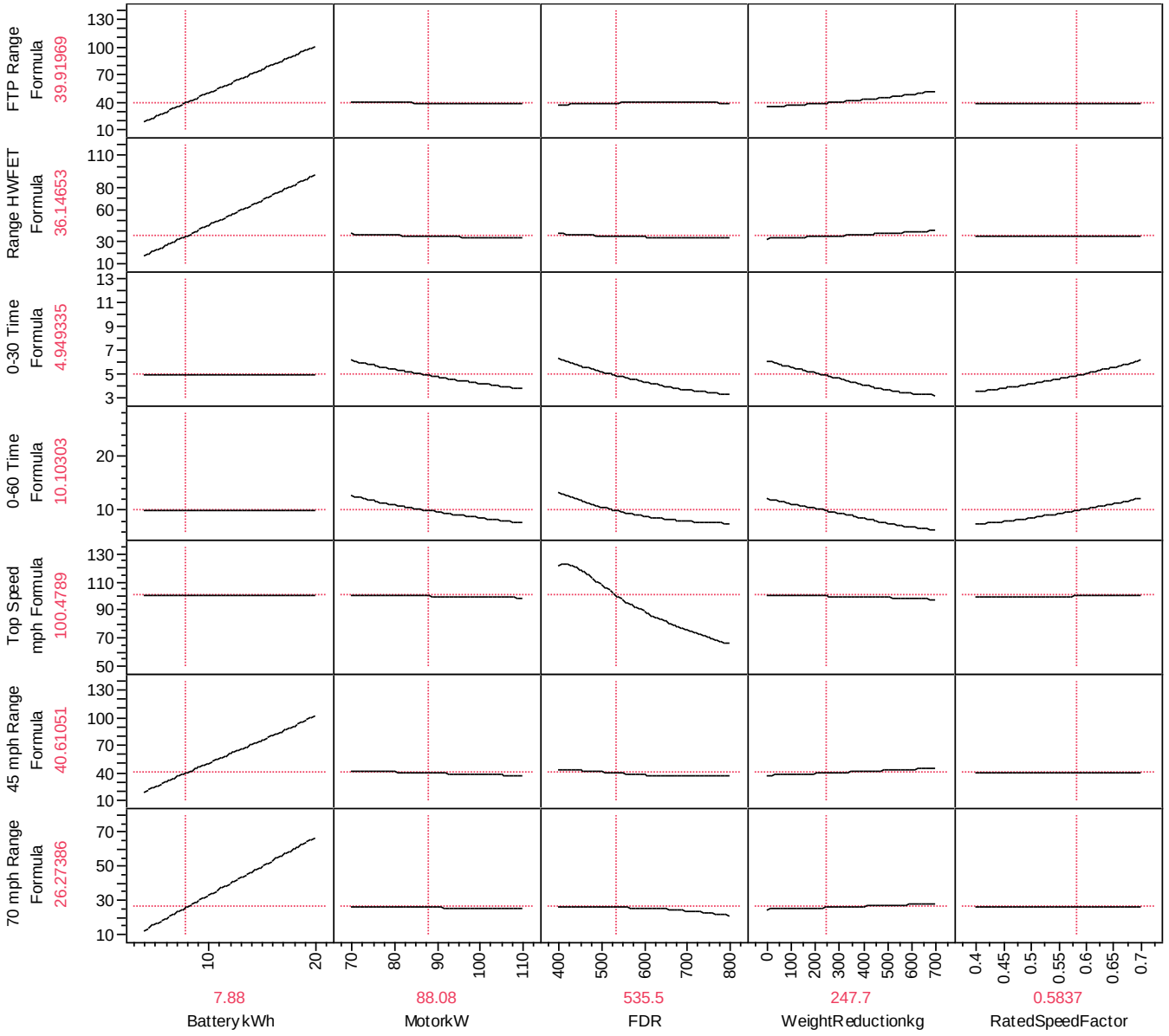
APPENDIX A – RESPONSE SURFACE PREDICTIONS PLOTS

Appendix A: Small Car – Case 1 [40 mi]



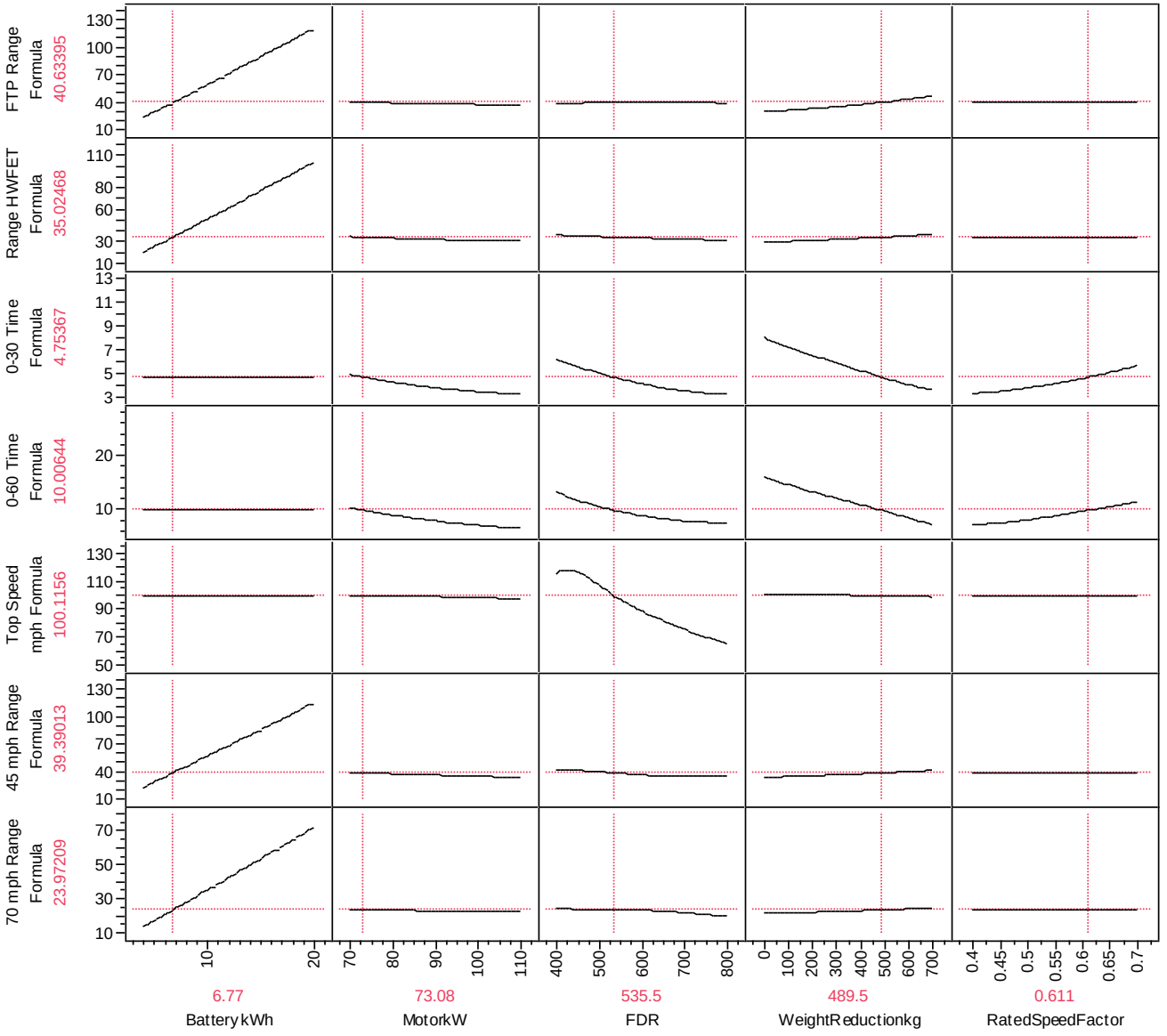
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 2 [40 mi]



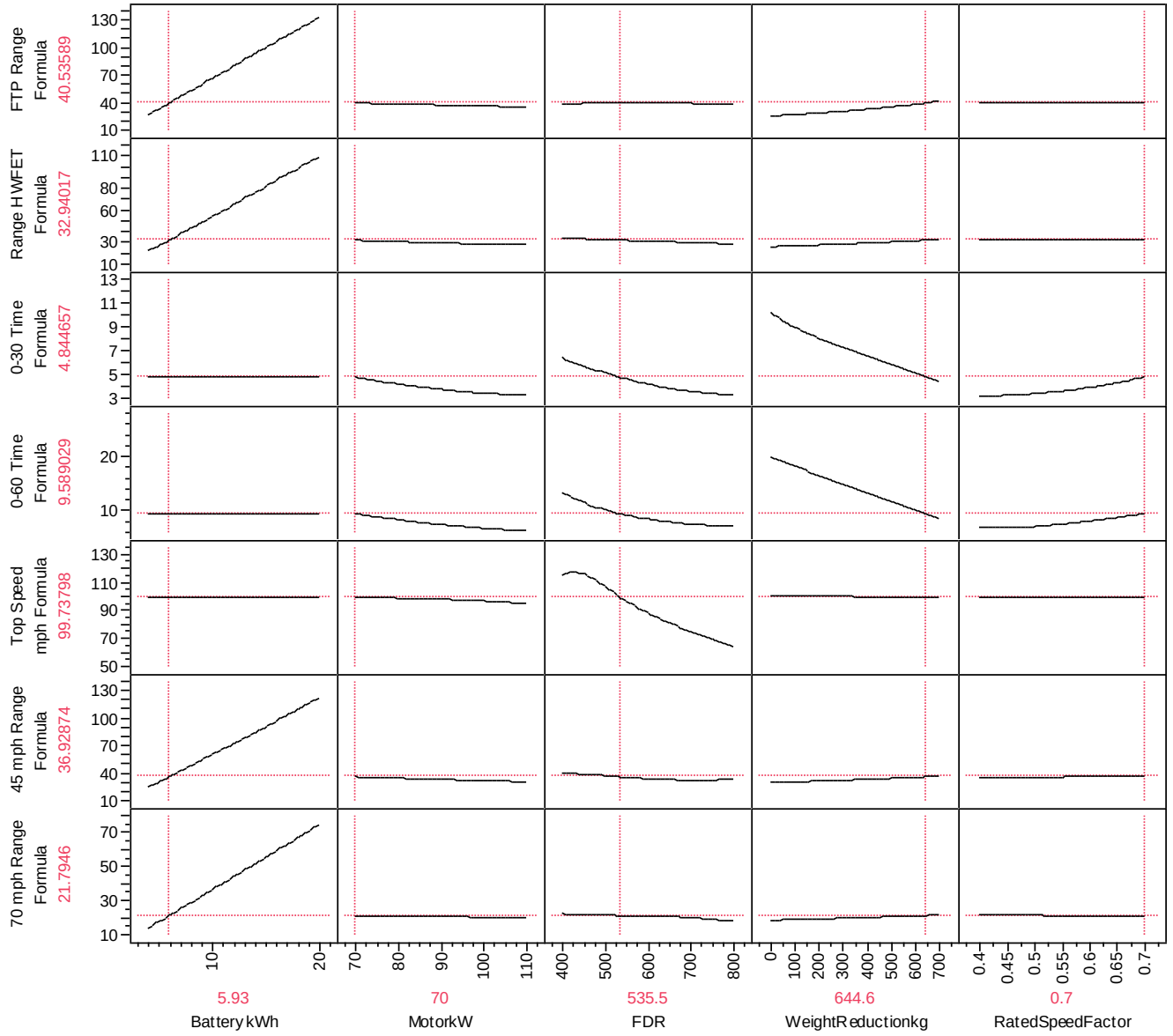
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 3 [40 mi]



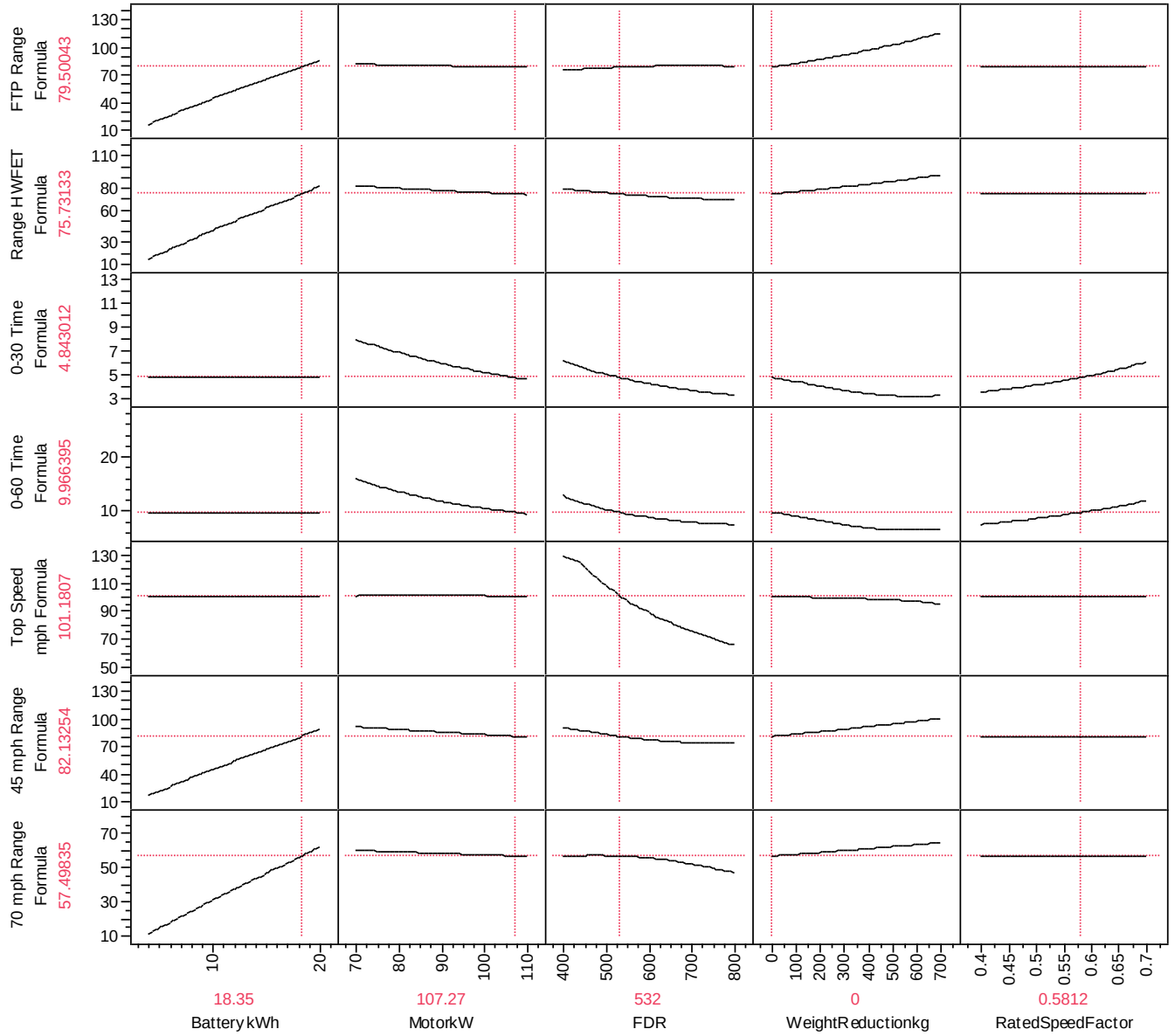
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 4 [40 mi]



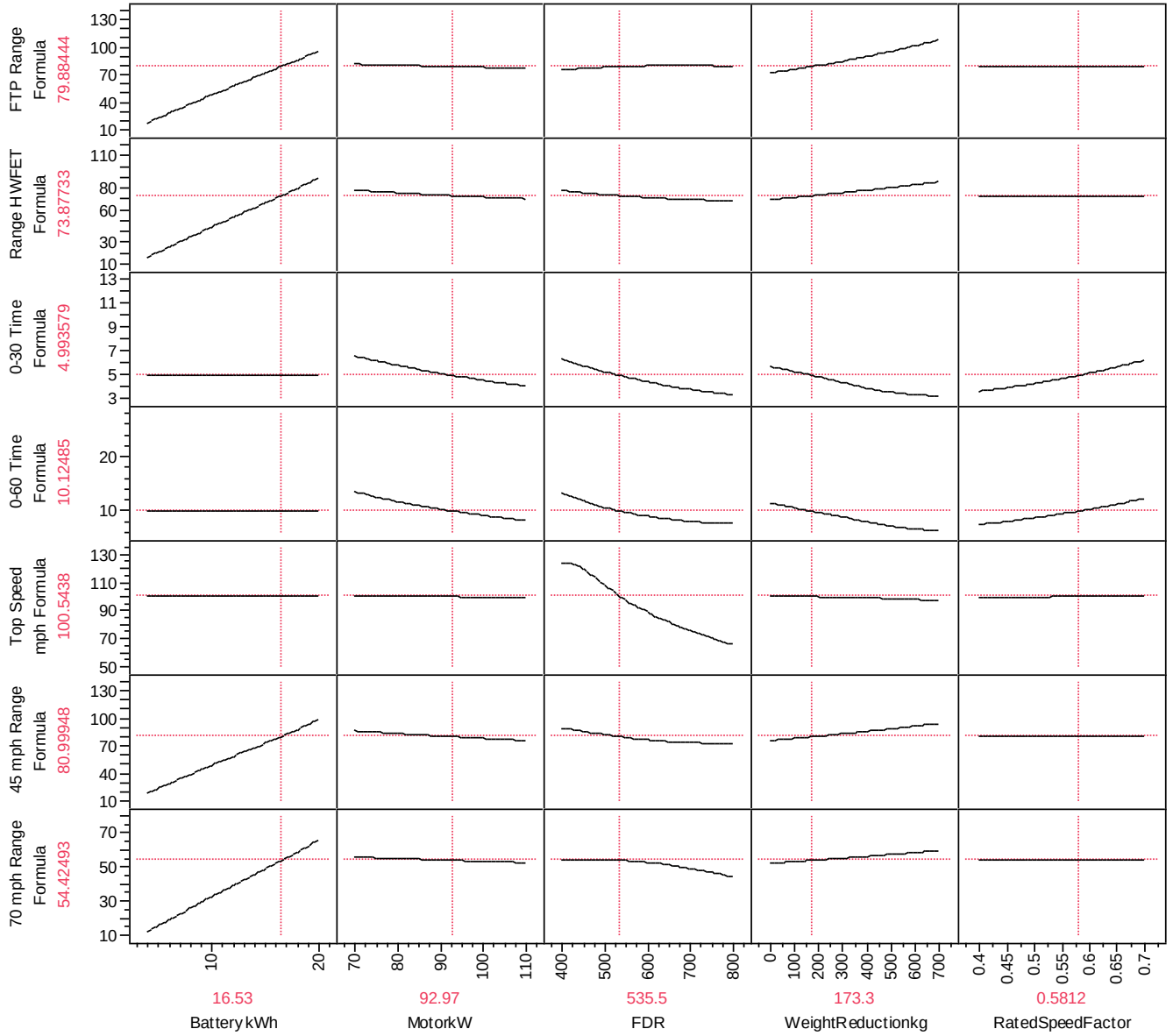
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 1 [80 mi]



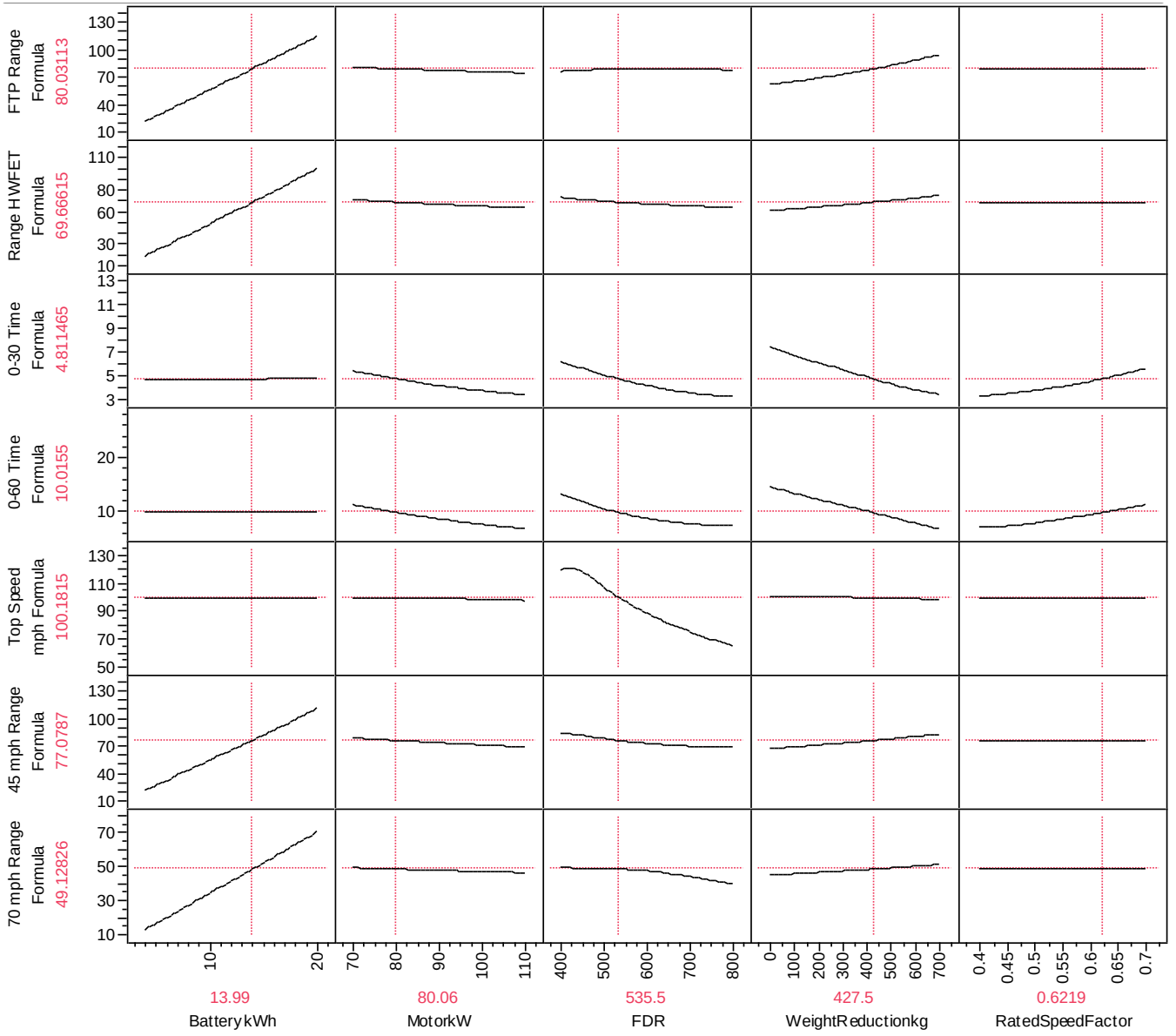
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 2 [80 mi]



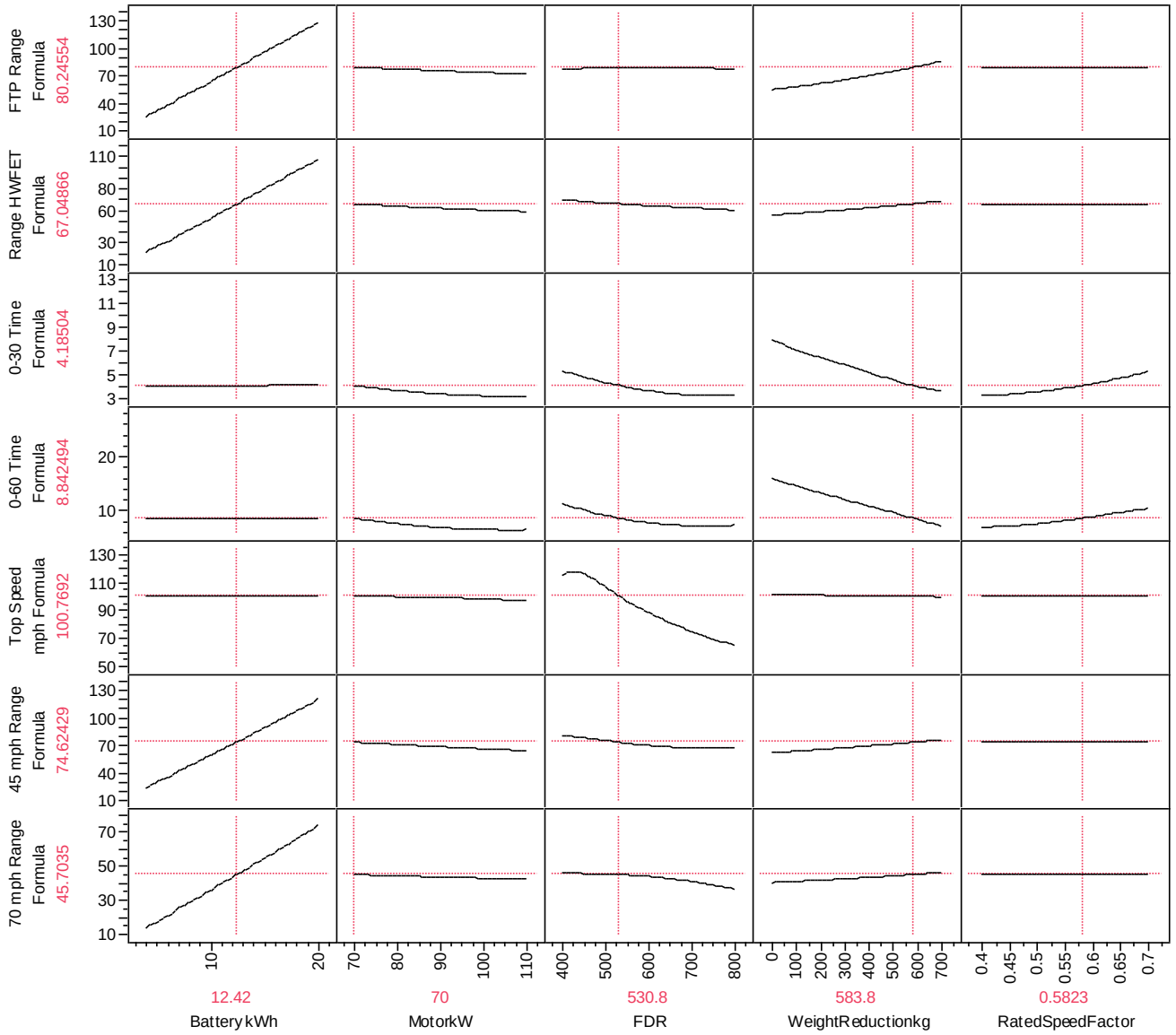
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 3 [80 mi]



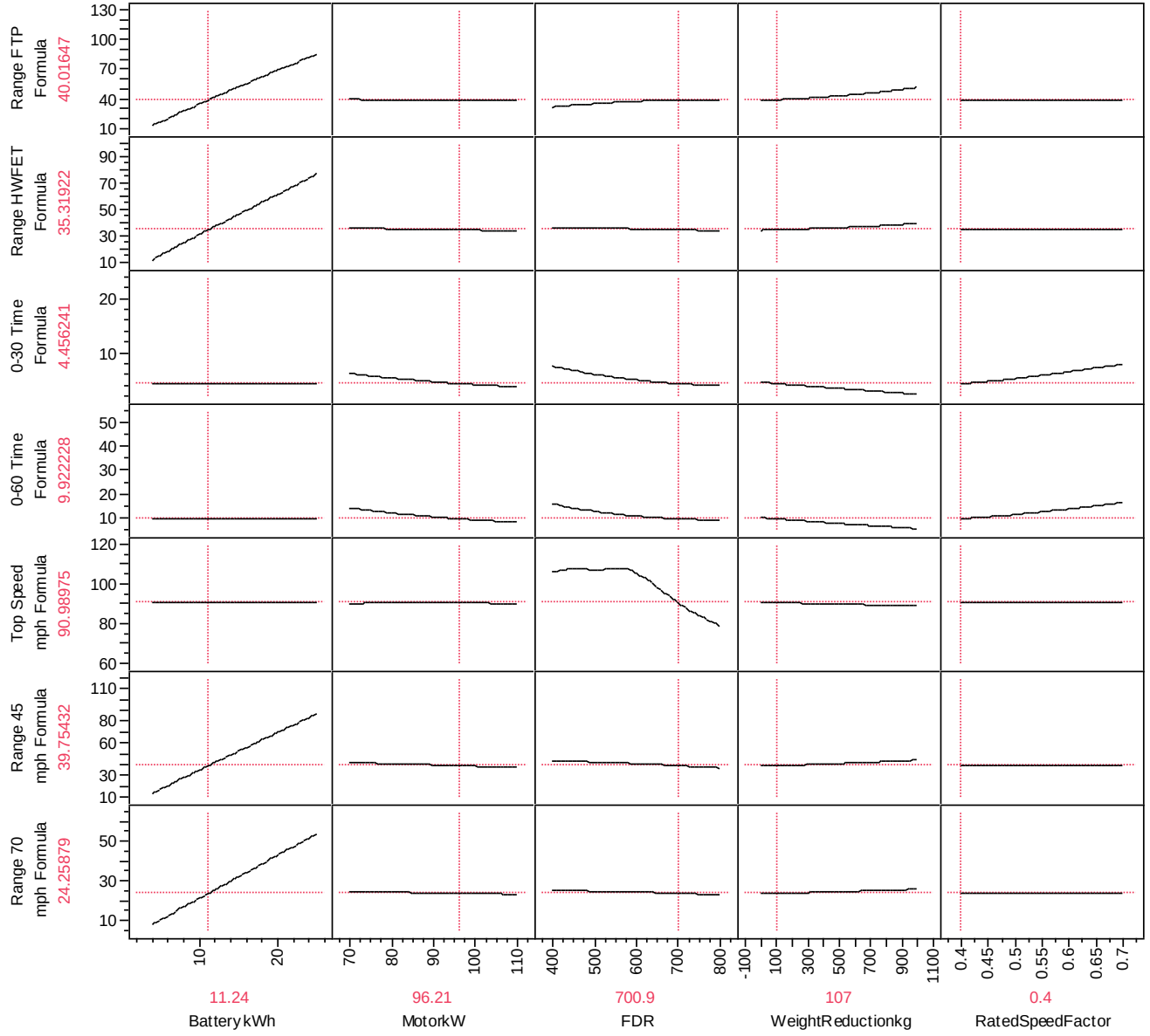
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small Car – Case 4 [80 mi]



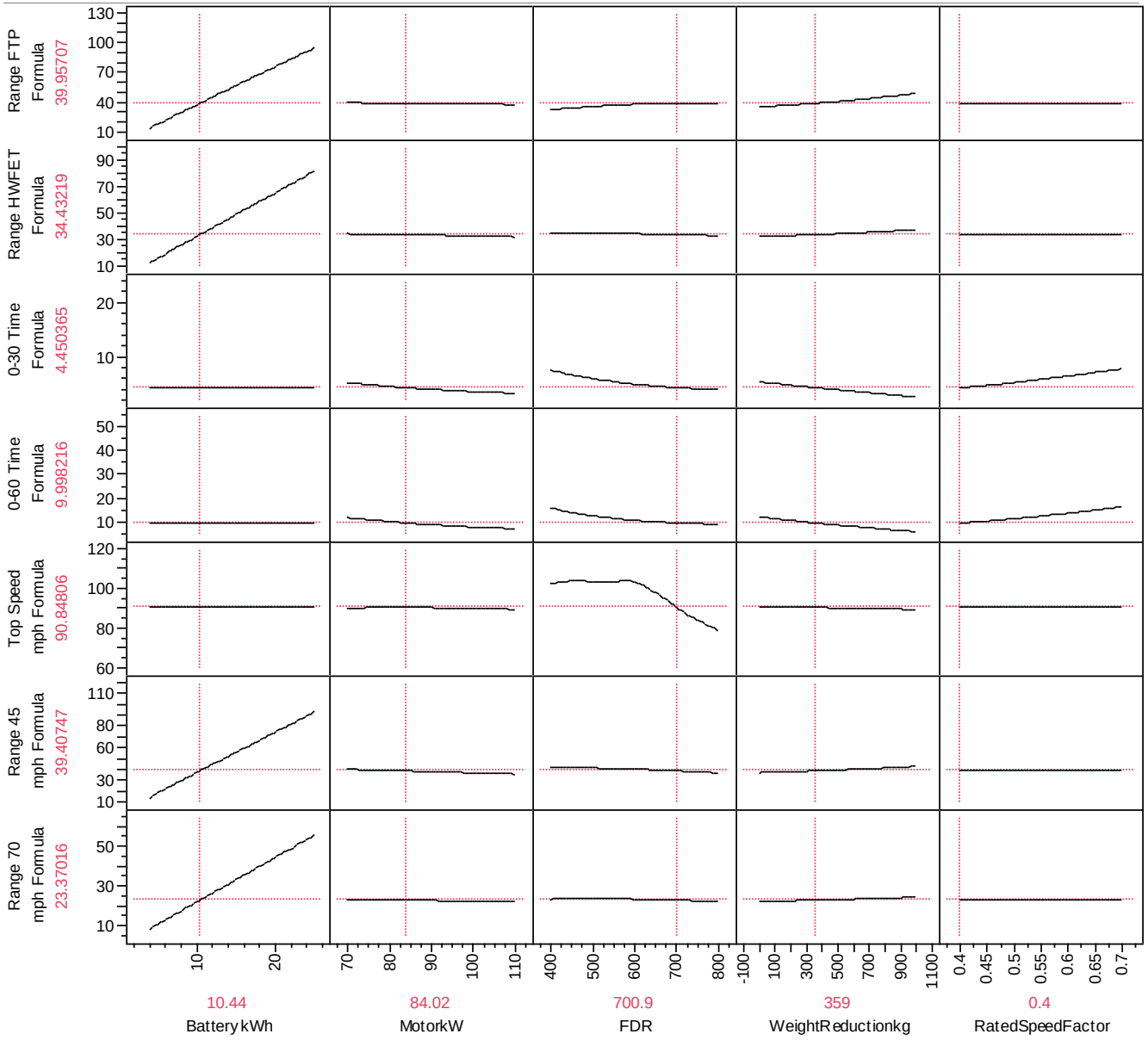
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 1 [40 mi]



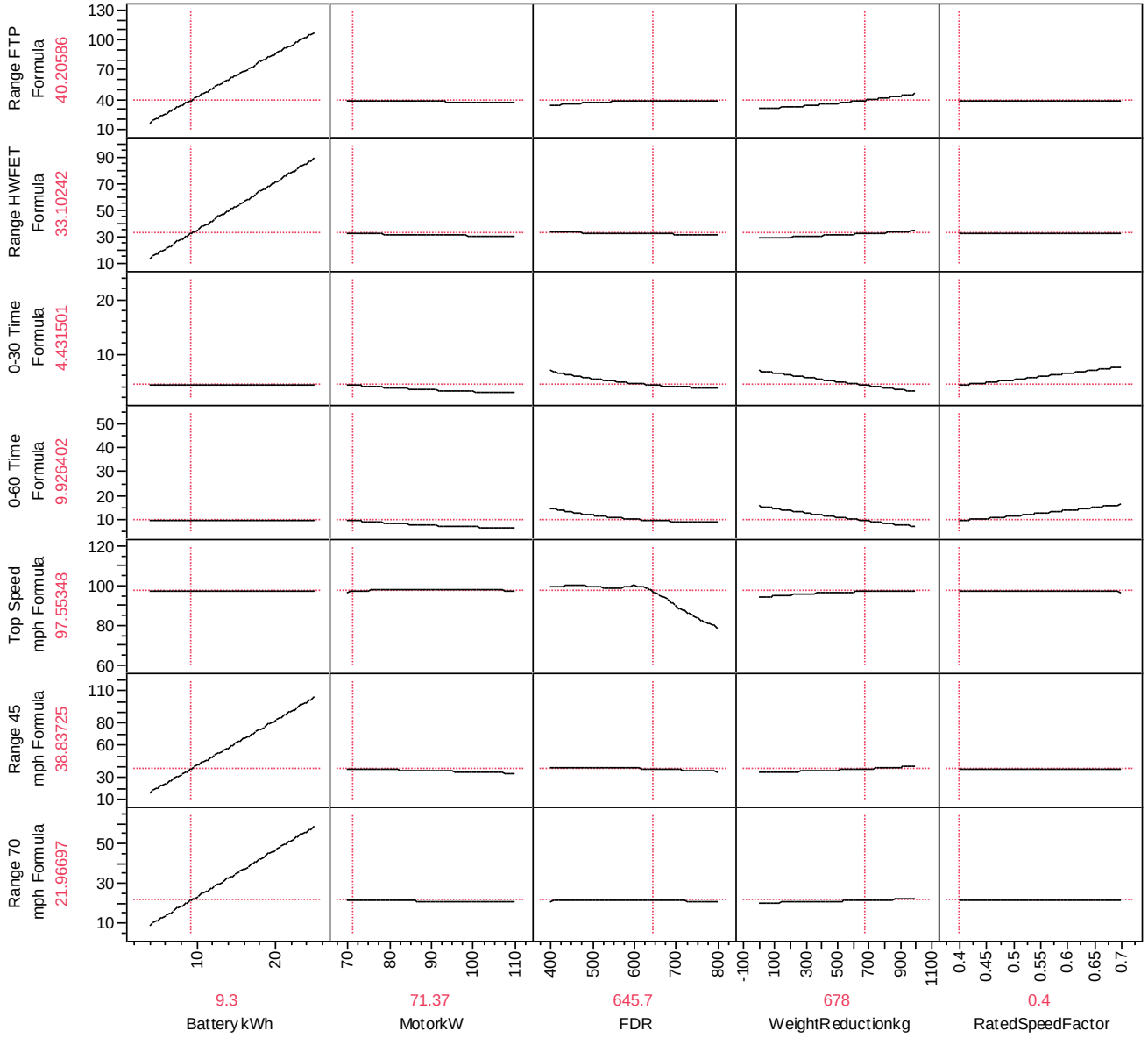
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 2 [40 mi]



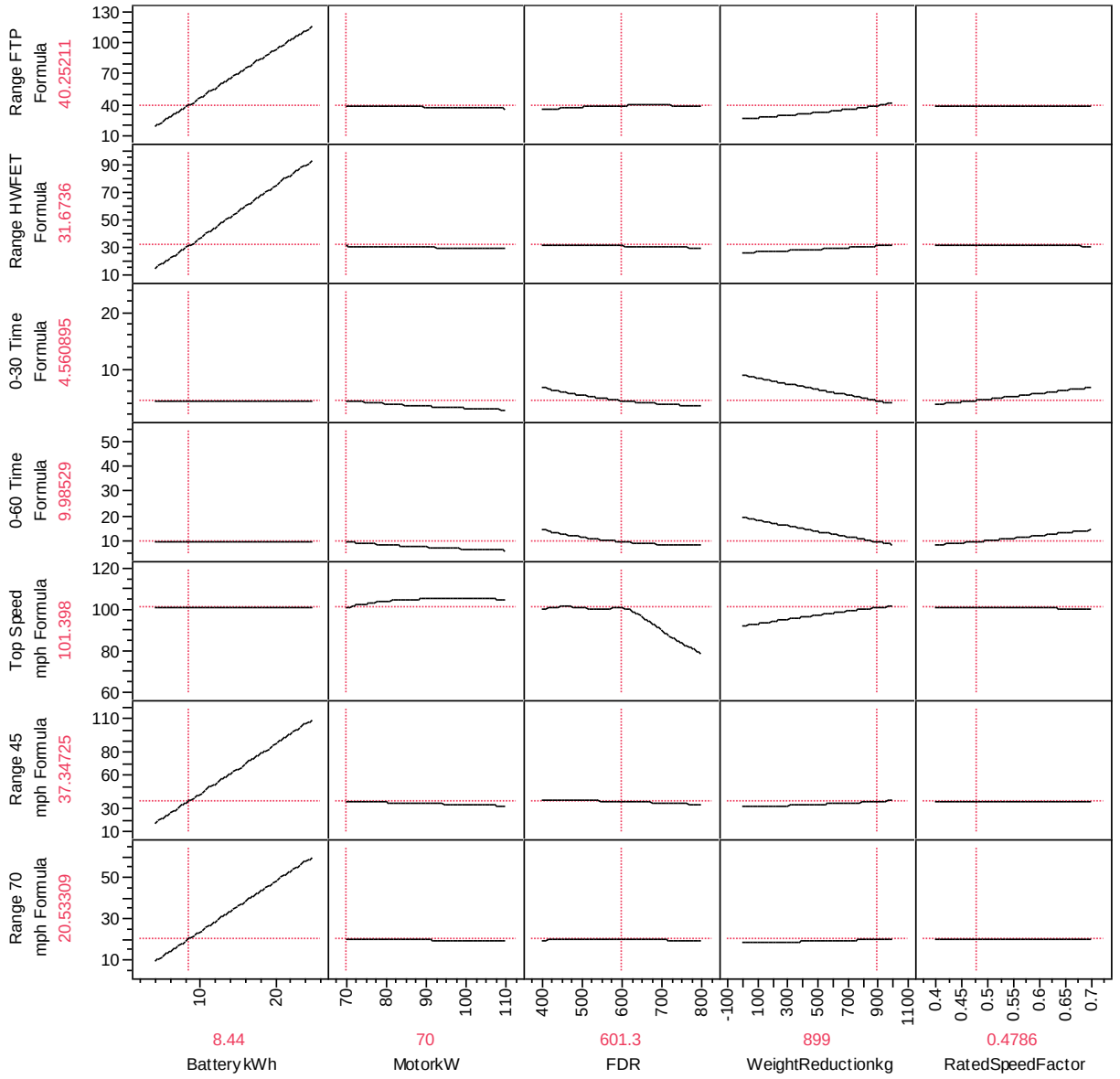
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 3 [40 mi]



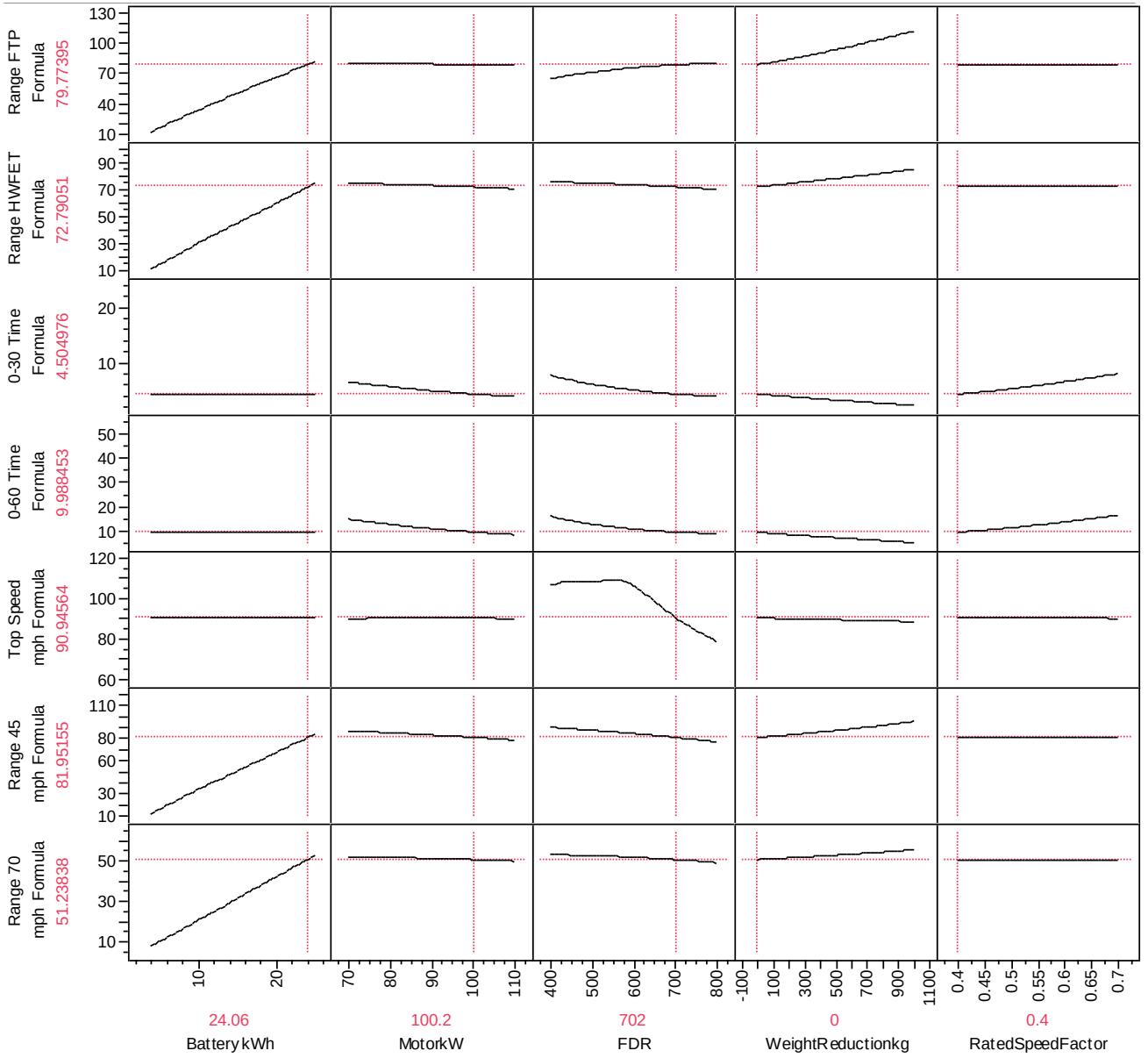
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 4 [40 mi]



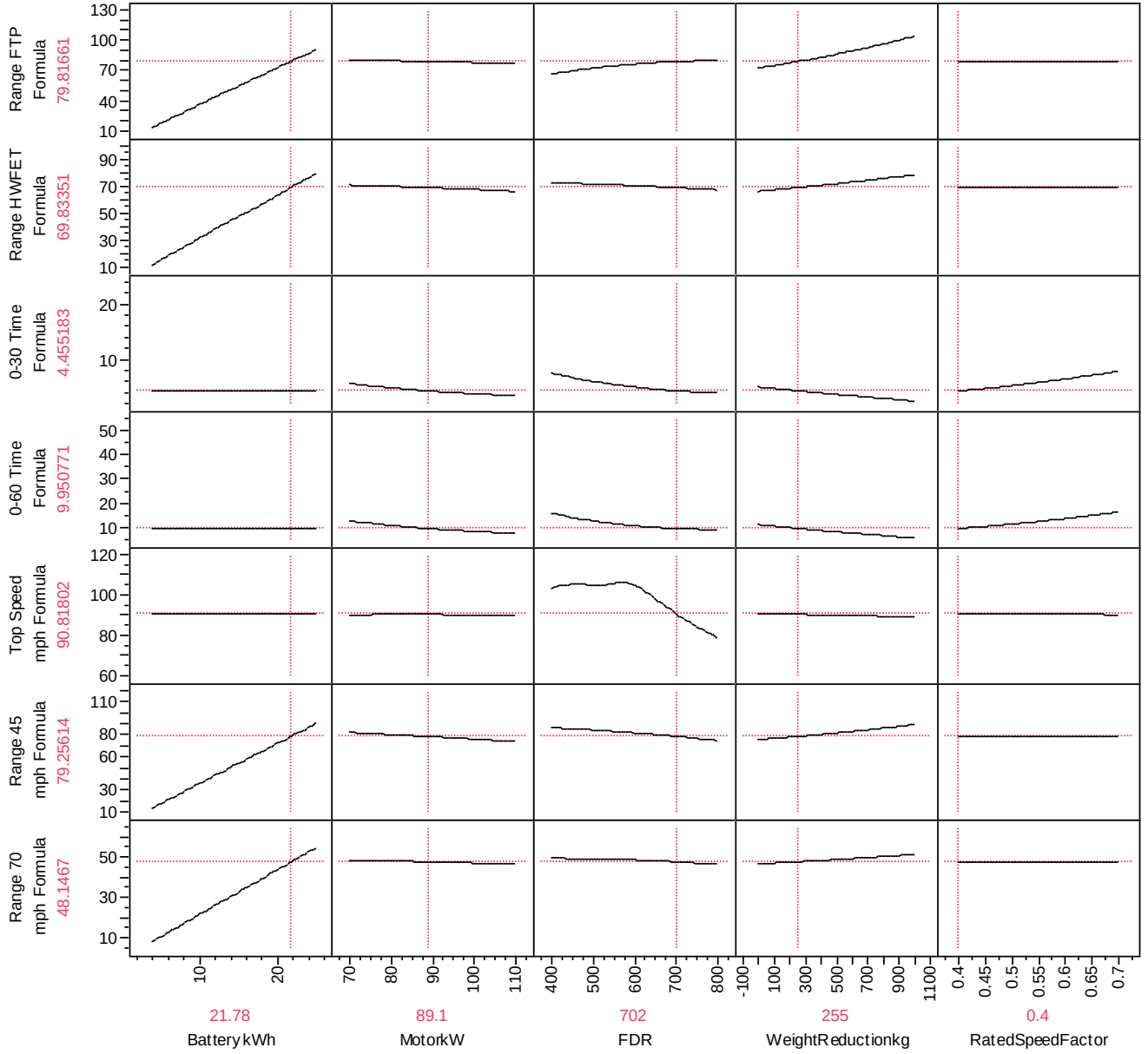
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 1 [80 mi]



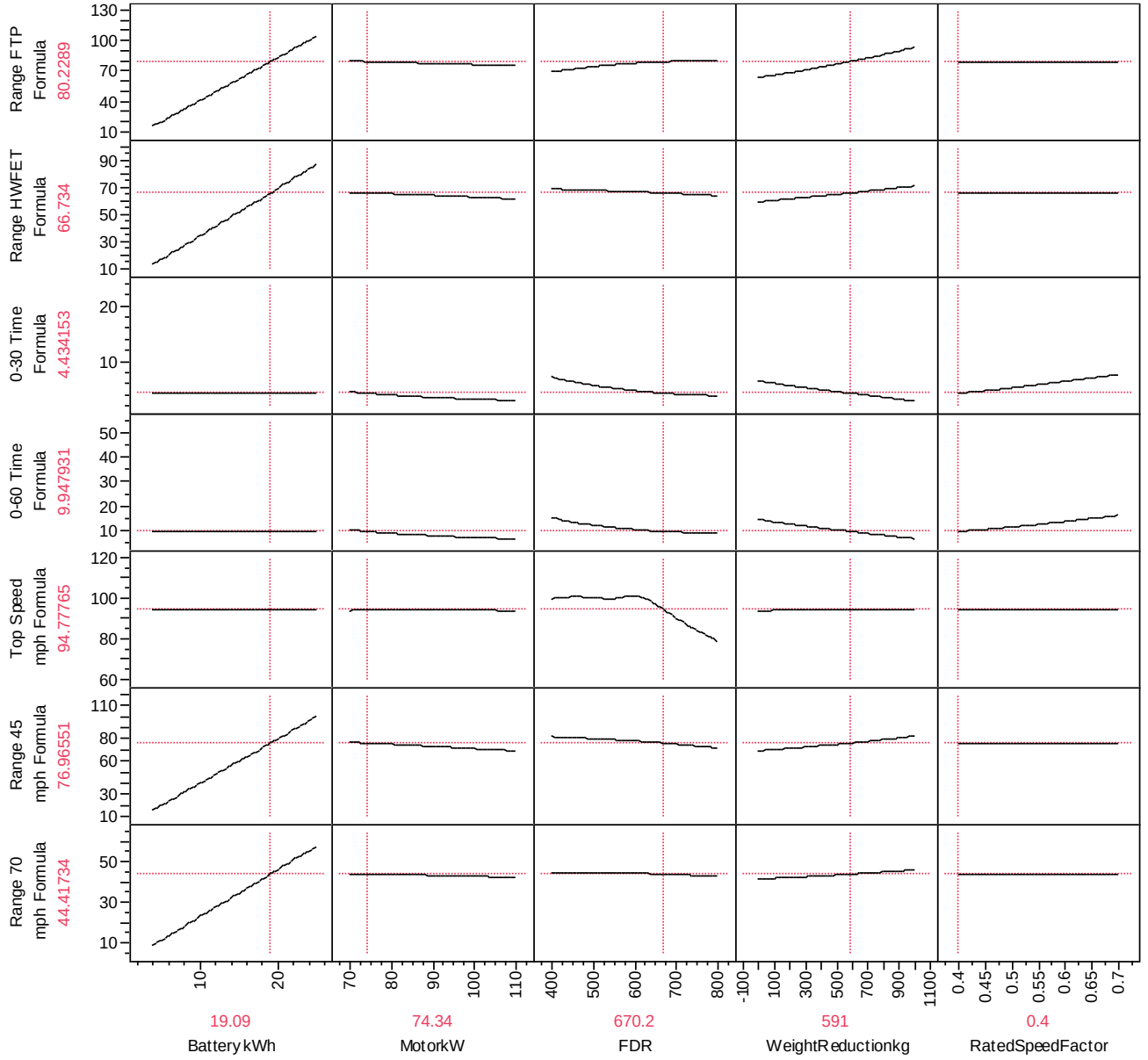
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 2 [80 mi]



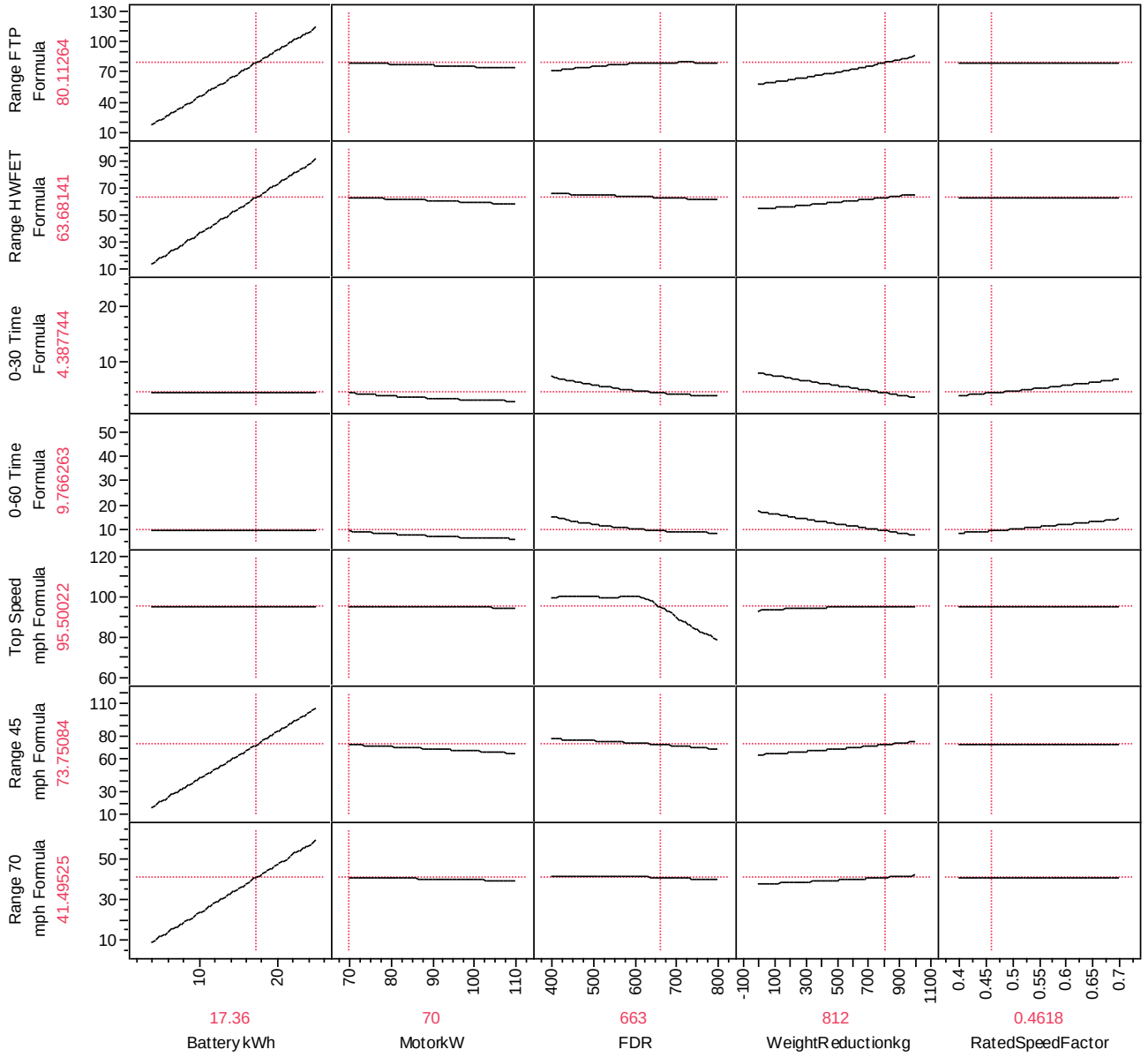
Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 3 [80 mi]



Note: Battery size is Usable kWh
RSM R^2 = 0.99

Appendix A: Small SUV – Case 4 [80 mi]

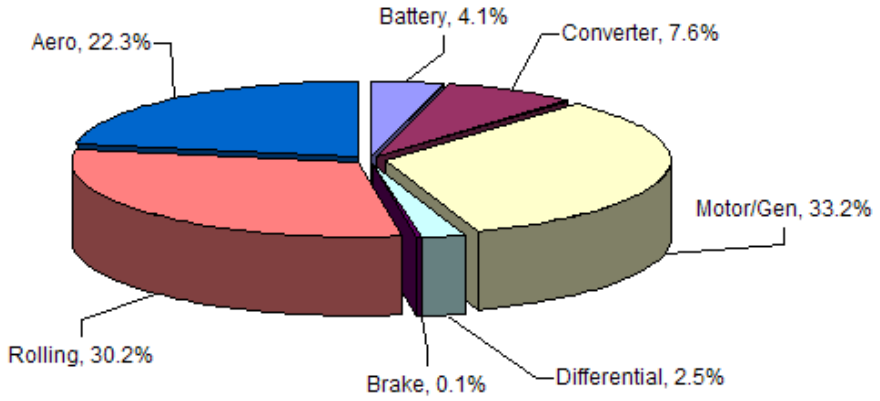


Note: Battery size is Usable kWh
RSM R^2 = 0.99

APPENDIX B –
ENERGY USAGE FTP vs. HWFET

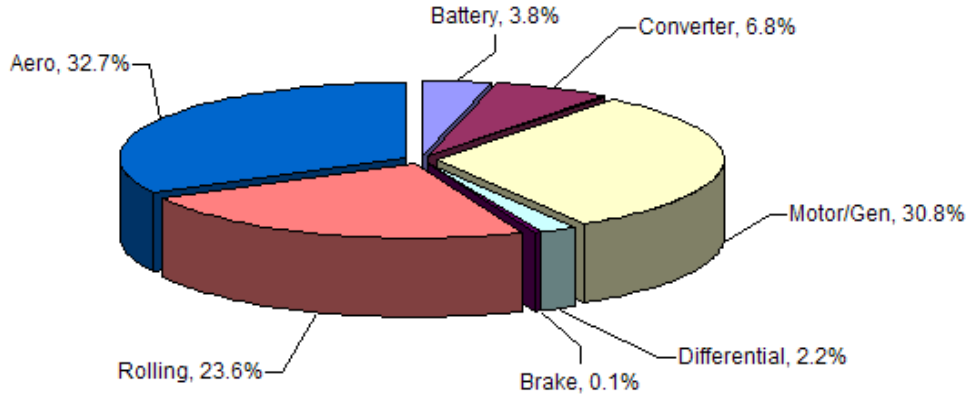
HWFET & FTP Energy Usage

Small Car, FTP75, Case 1: 1205 kg
[Regen = 20.9%]

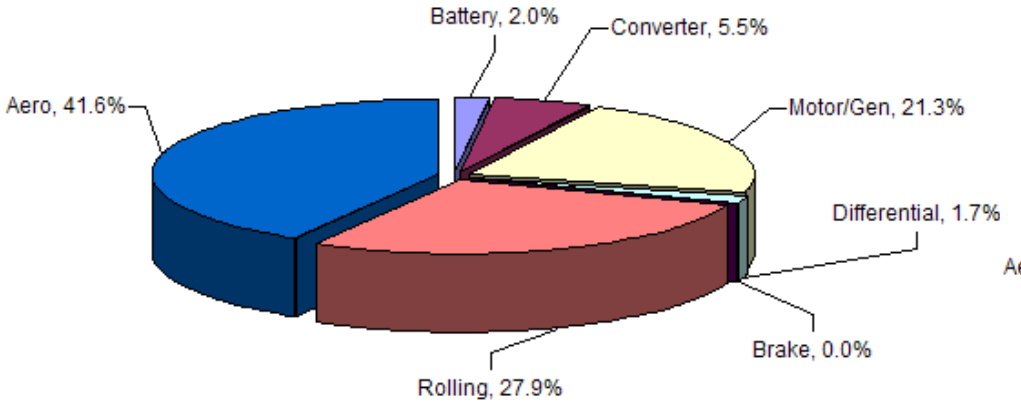


1265 kJ Lower Rolling Resistance
[over 1 FTP75 cycle]

Small Car, FTP75, Case 4: 627 kg
[Regen = 15.6%]

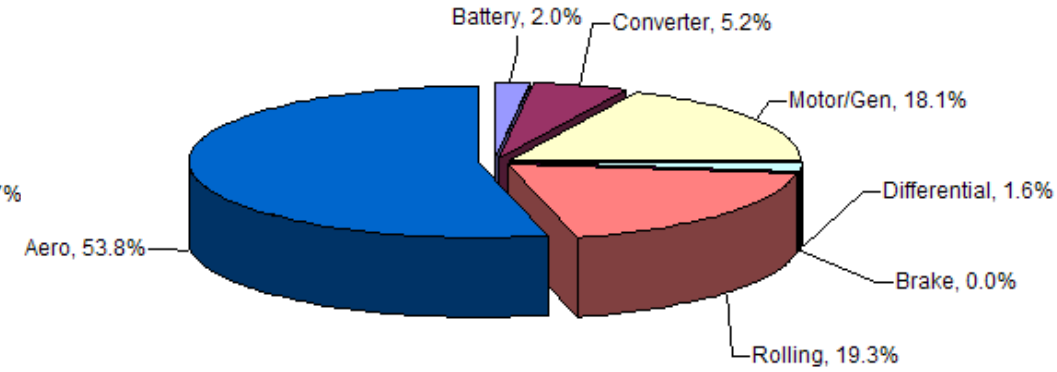


Small Car, HWFET, Case 1: 1205 kg
[Regen = 5.3%]



1130 kJ Lower Rolling Resistance
[over 1 HWFET cycle]

Small Car, HWFET, Case 4: 627 kg
[Regen = 2.8%]



APPENDIX C –
Brake Regeneration Plot

Small Car Brake Regen Example

The EV motor and battery size allow for large brake regeneration capture. No safety control was implemented and a fixed threshold was used to separate regen braking from mechanical braking.