Electric Vehicle Design

Design Problem – Fall 2024

Total Points Possible: 60

Your electric race team was recently awarded an $30,000 grant from Purdue to build a car to compete in a new electric race league. You already have a chassis, so this grant will go towards purchasing everything else necessary to make a competitive electric car. Use your knowledge from class to compare the different choices of motors, controllers, BMS's, and batteries that can be purchased online in order to design the ideal kart for this race. Be sure to consider everything from size, weight, functionality, price, and durability to guarantee that your car abides by the racing rules and will complete the race. **You may have to iterate a few times before finding a cell configuration that is ideal.** Feel free to use different color font to differentiate between iterations. (you may have to return to question 9 and do the math again with different parallel – series assumptions)

NOTE: Knowing your racecourse is critically important. Road courses are more technical and require more braking than oval courses. The increased braking results in more energy consumed per lap. Ovals may also require higher power from the motor since the throttle is more "wide open" throughout the course than compared to a road course. **For this project, assume the track is a road course similar to the technical nature of Purdue's Grand Prix track (photo to the right).**

Details:

- Race will be a road course that lasts **140 laps. Each lap is 1.25 miles**
  - The design of this race is more focused on endurance than sprint.
  - Maybe we call this race the Boiler Endurance 175!
- Unlimited pit stops are allowed
- Assume the rolling chassis is **500 lbs** (no driver, no battery pack).
- Assume packaging weight for the battery cells is about 50% of the cell weight. Therefore, a full battery pack would be 1.5 times the weight of individual cell weights added up.
  - Total Battery Pack Weight = 1.5 x [Sum of all cell weights]

- Energy consumed per lap is a critical piece of information that would normally be tested and measured. This number can vary based on factors such as driving style, how technical the track is (number of turns), yellow vs. green laps during the race, and – of course - kart setup. You will need to make an assumption about how many watt-hours your car will consume per lap. You may deduce this assumption two different ways through data that you have access to. See below.

  - <u>Using evGrand Prix data:</u>
    - The Purdue track is 0.27 miles long. Assume an evGP kart with no battery pack and no driver weighs 120 lbs. We know that evGP karts consume about 30 to 60 watt-hours for every lap around the Purdue track. Use this information to deduce an estimated watt-hours per lap for your vehicle. **Explain and defend your calculation in question 5 below.**
    - HINT: The course is 4.6x longer than the evGrand Prix track. What is the difference in weight of the vehicle? A vehicle twice the weight is not twice as inefficient, so do not reduce efficiency in a 1:1 ratio with weight. What are the technical differences between the evGrand Prix track and this proposed track (number of turns).

  - <u>Using Tesla Data:</u>
    - Tesla's average 300 watt-hours-per-<u>mile</u>, but that metric is not taken on a technical racecourse under racing conditions. However, a Tesla is much heavier. So, these factors may cancel out. In question 5 below, explain your reasoning with how you will use the Tesla data to deduce a watt-hours per <u>lap</u> for your vehicle.

Racing Rules:

- Energy onboard the car shall not exceed 25 kWh. Batteries may be swapped during pit stops.
- Kart DC power shall not exceed 50 kW from the battery
- Voltage on a battery pack shall not exceed 200 volts
- Weight of the battery pack will not exceed 50% of the total kart weight (no driver)
    - Battery Pack Total Weight =< Weight of Kart without Battery Pack or Driver

Short Answer Questions:

Include your math or briefly describe the factors that you used to determine each answer. Graded for accuracy and clarity of thought, not graded for grammar or formatting. Just get your point across clearly.

Your battery pack design must **balance power and energy effectively**. If your design comes out too lopsided then please re-iterate and do different design (usually this means a different battery cell). For example, you should not design a battery pack that can do 80 kW of power if the race rules state 15 kW is the maximum. This is because the power-dense cells in your poorly design pack would have less Ah-per-cell, therefore you are likely using more cells in your pack(s) than compared to a pack with a more balanced design.

1) Choose a type of motor, brand of motor, and list the actual model / part number of the motor you chose. Include the link to where you would buy it from. (3 points)
    a. Iteration #1
        i. Type of motor → Brushless DC Motor (BLDC)
            1. Lower maintenance compared to Brushed DC, since BLDC does not contain any brushes (brushes lead to higher resistance and more losses and wear due to presence of moving mechanical components)
        ii. Brand of Motor
            1. Motenergy
        iii. Model/Part Number
            1. ME1716
        iv. Link
            1. https://www.thunderstruck-ev.com/me1718.html
    b. Iteration #2
        i. I will keep same motor choice as Iteration #1
    c. Iteration #3
        i. Same as Iteration #1
    d. Iteration #4
        i. Type of motor → Brushless DC Motor (BLDC)
        ii. Brand of Motor
            1. Motenergy
        iii. Model/Part Number
            1. ME2011
        iv. Link
            1. https://www.thunderstruck-ev.com/motenergy-me2011-sealed-brushless-clone.html
        v. Reason for change:
            1. This motor accommodates higher voltages, as this one will use a higher voltage than the last iteration
    e. Iteration #5
        i. Same as #4

2) What is the top RPM speed of this motor? What is the max voltage and current of the motor? Be sure to clarify continuous versus peak currents, if the datasheet gives them. (3 points)
    a. Iteration #1
        i. Note: All information taken from thunderstruck motors website, which may not match other websites
        ii. Top RPM speed: 4500 RPM

        iii. Max Voltage: 48 Volts
            1. Range was provided from 24 – 48V
        iv. Currents:
            1. Peak: 300 A
            2. Continuous: 80 A
    b. Iteration #2
        i. Due to keeping the motor choice the same, these parameters will also remain the same
    c. Iteration #3
        i. Due to keeping the motor choice the same, these parameters will also remain the same
    d. Iteration #4
        i. Note: All information taken from thunderstruck motors website, which may not match other websites
        ii. Top RPM speed: 4200 RPM
        iii. Max Voltage: 72 Volts
            1. Range was provided from 48 – 72V
        iv. Currents:
            1. Peak: 600 A
            2. Continuous: 200 A
    e. Iteration #5
        i. Same as #4

3) What controller would you choose? Include a link to where you would buy it from. (2 points)
    a. Iteration #1
        i. Controller:
            1. Sevcon Gen4 S2 36/48V 275A SIN/COS-UVW-ACI Motor Controller 634A42206
        ii. Link:
            1. https://www.electricmotorsport.com/sevcon-gen4-36-48-275-1607.html
    b. Iteration #2
        i. Controller:
            1. Sevcon Gen4 S4 72-80V 350A SIN/COS-UVW-ACI Motor Controller 634A83207
        ii. Link:
            1. https://www.electricmotorsport.com/ev-parts/controllers/brushless-motor-controllers/sevcon-gen4-72-80v-350a.html
        iii. Why I went with this one:
            1. This motor controller is more ideal, as it can accommodate a higher voltage, which is more suitable in this application. In addition, the previous one may have been operating towards the top end of the voltage range which is not ideal the way I view it.
    c. Keeping this the same as Iteration #2
    d. Iteration #4
        i. Controller
            1. 634A13210 : Sevcon 96/120V 300A Gen 4 Size 4 Sin/Cos Controller
        ii. Link
            1. https://www.cloudelectric.com/product-p/54-634a13210.htm
        iii. Why I chose this one?
            1. Higher range of operating voltages
    e. Iteration #5
        i. Same as #4

4) What is the max current and voltage of this controller? Be sure to dig into the data sheet and show what the true max and min voltage are (not just the listed specs in the title)(2 points)
    a. Iteration #1
        i. Nominal Voltage:
            1. 36 – 48 V
        ii. Operating Voltage: (from product specification page, with confirmation from what is on datasheet)

            1. 19.3 – 69.6 V
        iii. Max Current
            1. 275 A (120 seconds)
            2. 330 A (10 seconds) → boost mode
    b. Iteration #2
        i. Nominal Voltage:
            1. 72 – 80 V
        ii. Operating Voltage: (from product specification page, with confirmation from what is on datasheet)
            1. 39.1 – 116 V
        iii. Max Current (single traction size 4)
            1. 350 A (120 seconds)
            2. 420 A (10 seconds) → boost mode
    c. Keeping this the same as Iteration #2
    d. Iteration #4
        i. Nominal Voltage:
            1. 96-110 V
        ii. Operating Voltage: (from specification sheet)
            1. 48 V to 150 V
        iii. Max Current
            1. 300 A peak
            2. 120 A continuous
    e. Iteration #5
        i. Same as #4

5) Declare what watt-hours per lap you will use in your design calculations. Use the information above to describe why you chose this number. Did the evGrand Prix data come up with similar results as the Tesla data? Why do you believe your vehicle will consume this many watt-hours per lap. (4 points)
    a. Iteration #1
        i. Using the evGP specs (120 lbs no driver and battery, 30 to 60 watt hours per lap, Lap Length is 0.27 miles) and information provided about this design problem (500 lbs rolling chassis, lap length 1.25 miles long, lap technicality is similar to Purdue GP) a good answer can be provided. The vehicle is about 4 times the weight, but not 4 times as inefficient. The Purdue GP track has 8 turns, while the new track (assuming similar technicality) would have about 40 turns. This requires more watt hours per lap.
        ii. Given all of the factors, let's assume a sufficient number to be **<u>300 Wh per lap</u>**
            1. Lap length is 4.6x (300/60 is 5)
            2. Weight is up by factor of around 4, while Watt hours would be up by a factor of 5-10.
            3. This number closely matches what the Tesla data provides. Tesla data would suggest a 375 Wh per lap, while being much heavier. Due to the relative lightness of this vehicle, 300 Wh seems reasonable (especially considering racing scenario, which Tesla data does not factor in)
            4. The last thing that I am using to draw this conclusion is the fact that I am assuming the race is running under green flags the entire time and the driver is also very aggressive in pushing the kart to its limits
    b. Iteration #2
        i. I believe that the value I have deduced is still accurate according to the logic dictated above
    c. Iteration #3
        i. After two iterations of thought, this is definitely worth a revisit. I technically looked at the max capacity in all scenarios, where the driver would be pushing to the limit at all times. This is also an incorrect assumption, as that might induce human error, and is not physically possible to do; mistakes are inevitable.
        ii. Let's justify this
            1. Per the evGP data given, the track is almost 5x longer, and the vehicle is 4x the weight (compared to that). This does not correspond to a system that is 4x as

inefficient. Instead of looking at the top end range provided for evGP, it is best to take a number that is closer to the top, but not at the top fully. A number like 45 would work. Now scaling up 45 Wh to about 250 Wh would make sense. This would be more than 5x. The Watt hours would also scale up by 4-8x, which does provide some leeway in that regard as well.

2. Per the Tesla data, this would also make sense, since a Tesla would require 375 Wh, it would make sense for this to be much lower than that since this would and should hypothetically weigh a lot less

iii. On top of this justification, there are bound to be moments of chaos on the track where there are yellow flags and such and also the driver will not be pushing flat out all the time

iv. Value chosen:

1. **250 Wh per lap**

d. Iteration #4

i. Same as #3

e. Iteration #5

i. Same as #4

6) How much energy do you estimate you will need to complete the race? Have you accounted for voltage sag during lower SOC's? (2 points)

a. Iteration #1

i. Given 140 lap race, 1.25 miles per lap, 300 watt-hours per lap:

1. $140\ laps * \frac{300\ Wh}{lap} = 42{,}000\ Wh = 42\ kWh$

ii. To remain competitive during lower SOC's, add 30% to it

1. $42\ kWh * 1.3 = \mathbf{54.6\ kWh}$

b. Iteration #2

i. This value remains unchanged since the energy usage per lap has not changed

c. Iteration #3

i. Given 140 lap race, 1.25 miles per lap, 300 watt-hours per lap:

1. $140\ laps * \frac{250\ Wh}{lap} = 35000\ Wh = 35\ kWh$

ii. To remain competitive during lower SOC's, add 30% to it

1. $35\ kWh * 1.3 = \mathbf{45.5\ kWh}$

d. Iteration #4

i. Same as #3

e. Iteration #5

i. Same as #4

7) What nominal voltage will you choose for your design? Explain your reasoning for choosing this voltage. (4 points)

a. Iteration #1

i. Motor controller is Sevcon Gen4 series, need 14S minimum

ii. Orion Jr BMS is ideal for its lower price, which requires a 16S maximum

iii. Let's use a battery pack that would have 16S, assuming regular 18650:

1. $16\ cell * \frac{3.6\ V}{cell} = \mathbf{57.6\ V}$

a. Operating under assumption that nominal voltage is 3.6 V

b. Iteration #2

i. Motor controller still requires a 14s minimum, however, more cells can be put in series. This is because the window has been widened and increasing this value would reduce the number of cells required in parallel (optimizing this can very much help the battery size limitation)

ii. While it would have been nice to use the Orion Jr BMS, this changed can be justified by reducing the cost of the batteries significantly as well as an improved performance and compliance to rules

iii. Let's use a battery pack with 24 cells in series, and assuming 3.6 V for nominal:

1. $24\ cell * \frac{3.6\ V}{cell} = \mathbf{86.4\ V}$

c. Iteration #3
   i. I'll keep this the same as iteration #2
d. Iteration #4
   i. I will increase this from iteration #2 to be 30 cells in series
      1. $30\ cell * \frac{3.6\ V}{cell} = \mathbf{108\ V}$
e. Iteration #5
   i. Same as #4

8) What battery chemistry will you choose for this application? What battery format would you choose? (Format = physical shape/dimension). Why did you choose this cell? Include a link to a potential vendor of this battery cell. **Include a link to the cell's data sheet.** (4 points)
   a. Iteration #1
      i. Battery Chemistry
         1. 18650 Li-Ion
      ii. Format:
         1. Prismatic
      iii. Justification:
         1. The 18650 Li-Ion is a common pack that can be purchased for evGP, hence that was used
         2. The prismatic format is easier to assemble in a pack and better for DIY applications. However, it is difficult to cool so depending on where this would be placed in the kart, might need a robust cooling system to be built around it
         3. The size of this battery also means that it weighs less per cell and can be assembled into a tighter packaging
      iv. Link to vendor:
         1. https://www.18650batterystore.com/products/panasonic-ncr18650ga-ga6
      v. Link to datasheet:
         1. https://cdn.shopify.com/s/files/1/0481/9678/0183/files/60f5bf9a9fbf95001ac60005-GA6W.pdf?v=1626883833
   b. Iteration #2
      i. Battery Chemistry
         1. 21700 Li-Ion
      ii. Format:
         1. Prismatic
      iii. Justification:
         1. This battery (linked below) improves on the last one by being of a higher capacity which can help keep costs and weight down
      iv. Link to vendor:
         1. https://www.18650batterystore.com/products/molicel-p45b
      v. Link to Datasheet:
         1. https://cdn.shopify.com/s/files/1/0481/9678/0183/files/INR21700P45B_1.2_Product-Data-Sheet-of-INR-21700-P45B-80109.pdf?v=1670425745
   c. Iteration #3
      i. Battery Chemistry
         1. 21700 Li-Ion
      ii. Format:
         1. Prismatic
      iii. Justification:
         1. Unlike iteration #2, this battery has MUCH lower discharge rates and is also of a higher capacity
      iv. Link to vendor:
         1. https://liionwholesale.com/products/vapcell-f60-21700-12-5a-flat-top-6000mah-battery-genuine?variant=40860573958213
      v. Link to Datasheet:
         1. https://www.vapcelltech.com/h-pd-202.html
            a. While this is not a data sheet (it is a link to the manufacturer's website), it has all relevant information needed

d. Iteration #4
    i. Same as Iteration #3
e. Iteration #5
    i. Same as #4

NOTE: Question 9 & 10 are concurrent questions. You may do them in any order, logically.

9) In order to finish the race, what configuration will you make the battery pack(s) if you were to use these cells? (How many in parallel? How many in series?) **Explain your reasoning for choosing this configuration.** Note: your design may use multiple battery packs. If this is the case, please declare that now. (6 points)
    a. Iteration #1
        i. Configuration Determination:
            1. Per the 300 Wh per lap value above and 140 laps… The requirement is to have 42 kWh, but 54.6 kWh to account for voltage sag
            2. This value higher than 25 kWh, so need multiple battery packs to finish the race
                a. Let's assume 25 kWh on board (for now to find actual max capacity on board)
            3. Pack Ah:
                a. $25000\ Wh / 57.6\ V = 434.02\ Ah$
            4. Number of Cells in Parallel:
                a. $434.02\ Ah / 3.45\ Ah = 125.8\ cells$
                    i. Rounding down to 125 cells
        ii. Configuration:
            1. 16s125p
    b. Iteration #2
        i. Configuration Determination:
            1. Requirement is still 54.6 kWh
            2. Multiple packs are still required
                a. Let's once again assume 25 kWh will be on board the car at any given moment
            3. Pack Ah:
                a. $25000\ Wh / 86.4\ V = 289.35\ Ah$
            4. Number of Cells in Parallel:
                a. $289.35\ Ah / 4.50\ Ah = 64.3\ cells$
                    i. Rounding down to 64 cells
        ii. Configuration
            1. 24s64p
    c. Iteration #3
        i. Configuration Determination:
            1. Requirement is 45.5 kWh
            2. Multiple packs are still required
                a. Let's once again assume 25 kWh will be on board the car at any given moment
            3. Pack Ah:
                a. $25000\ Wh / 86.4\ V = 289.35\ Ah$
            4. Number of Cells in Parallel:
                a. $289.35\ Ah / 6.00\ Ah = 48.225\ cells$
                    i. Rounding down to 48 cells
        ii. Configuration
            1. 24s48p
    d. Iteration #4
        i. Configuration Determination:
            1. Requirement is 45.5 kWh

2. Multiple packs are still required
   a. Let's assume 20 kWh will be on board the car at any given moment
3. Pack Ah:
   a. $20000\ Wh / 108\ V = 185.185\ Ah$
4. Number of Cells in Parallel:
   a. $185.185\ Ah / 6.00\ Ah = 30.86\ cells$
      i. Rounding up to 31 cells

ii. Configuration
   1. 30s31p

e. Iteration #5
   i. Configuration Determination:
      1. Requirement is 45.5 kWh
      2. Multiple packs are still required
         a. Let's assume 22 kWh will be on board the car at any given moment
      3. Pack Ah:
         a. $22000\ Wh / 108\ V = 203.7\ Ah$
      4. Number of Cells in Parallel:
         a. $203.7\ Ah / 6.00\ Ah = 33.95\ cells$
            i. Rounding up to 34 cells
   ii. Configuration
      1. 30s34p

10) How much energy will you have in each pack? How many packs will you need to complete the race? How many total cells are in each pack? (4 points)

a. Iteration #1
   i. Energy:
      1. $434.02\ Wh * \frac{57.6\ V}{pack} = 24999.5\ Wh\ or\ \mathbf{25\ kWh}$
   ii. How many packs?
      1. $\frac{54.6\ kWh}{25\ kWh} = 2.184 \rightarrow \mathbf{3\ battery\ packs}$
   iii. Total cells in each pack:
      1. $16 * 125 = \mathbf{2000\ cells}$

b. Iteration #2
   i. Energy:
      1. $289.35\ Ah * \frac{86.4\ V}{pack} = 24999.84\ Wh\ or\ \mathbf{25\ kWh}$
   ii. How many packs?
      1. $\frac{54.6\ kWh}{25\ kWh} = 2.184 \rightarrow \mathbf{3\ battery\ packs}$
   iii. Total cells in each pack:
      1. $24 * 64 = \mathbf{1536\ cells}$

c. Iteration #3
   i. Energy:
      1. $289.35\ Ah * \frac{86.4\ V}{pack} = 24999.84\ Wh\ or\ \mathbf{25\ kWh}$
   ii. How many packs?
      1. $\frac{45.5\ kWh}{25\ kWh} = 1.82 \rightarrow \mathbf{2\ battery\ packs}$
   iii. Total cells in each pack:
      1. $24 * 48 = \mathbf{1152\ cells}$

d. Iteration #4
   i. Energy:
      1. $185.185\ Ah * \frac{108\ V}{pack} = 19999.872\ Wh\ or\ \mathbf{20\ kWh}$
   ii. How many packs?
      1. $\frac{45.5\ kWh}{20\ kWh} = 2.275 \rightarrow \mathbf{3\ battery\ packs}$
   iii. Total cells in each pack:
      1. $30 * 31 = \mathbf{930\ cells}$

e. Iteration #5
   i. Energy:
      1. $203.7Ah * \frac{108\ V}{pack} = \mathbf{22\ kWh}$
   ii. How many packs?
      1. $\frac{45.5\ kWh}{22\ kWh} = 2.068 \rightarrow \mathbf{3\ battery\ packs}$
   iii. Total cells in each pack:
      1. $30 * 34 = \mathbf{1020\ cells}$

11) Given the cost of your individual cells, how much will it cost to buy all the cells needed to race in this competition? Do not include cost to assemble or package. Just include cost of the lithium cells. What is your dollar-per-kWh for the cells? (3 points)

a. Iteration #1
   i. Cells required → 2000
   ii. Cost of individual (given buying 2000) → $3.60
   iii. Cost of individual pack → $7200
   iv. Three packs would cost **$21,600**
b. Iteration #2
   i. Cells required → 1536
   ii. Cost of individual (given buying 1536) → $5.25
   iii. Cost of individual pack → $8064
   iv. Three packs would cost **$24,192**
c. Iteration #3
   i. Cells required → 1152
   ii. Cost of individual (given buying 1152) → $6.31
   iii. Cost of individual pack → $7269.12
   iv. Two packs would cost **$14,538.24**
d. Iteration #4
   i. Cells required → 930
   ii. Cost of individual (given buying 930) → $6.39
   iii. Cost of individual pack → $5942.70
   iv. Three packs would cost **$17,828.10**
e. Iteration #5
   i. Cells required → 1020
   ii. Cost of individual (given buying 1020) → $6.31
   iii. Cost of individual pack → $6,436.20
   iv. Three packs would cost **$19,308.60**

NOTE: Going forward, the questions will address **one single battery pack**. Your design may require multiple packs to finish the race (using pit stops to replace the battery pack) but the questions below will talk about an individual pack.

12) What are the discharge and charge rates for the cell you chose? How much energy does each cell have? What are the dimensions of each cell? What is the weight of each cell? (4 points)

a. Iteration #1
   i. Continuous Discharge: 10 A
   ii. Charge: 1.675 A
   iii. Nominal Ah per cell: 3.45 Ah
   iv. Nominal Voltage per cell: 3.6 V
   v. Min/Max Voltage per cell: 2.5 V / 4.2 V
   vi. Energy per cell:
      1. 3.45 Ah * 3.6 V = 12.42 Wh
   vii. Dimensions per cell: 18.33 mm by 65.08 mm
   viii. Weight per cell: 46.5 g
b. Iteration #2
   i. Continuous Discharge: 45 A

ii. Charge: 4.5 A (standard)
iii. Nominal Ah per cell: 4.50 Ah
iv. Nominal Voltage per cell: 3.6 V
v. Min/Max Voltage per cell: 2.5 V / 4.2 V
vi. Energy per cell:
1. 4.50 Ah * 3.6 V = 16.2 Wh
vii. Dimensions per cell: 21.55mm by 70.15mm
viii. Weight per cell: 70g

c. Iteration #3
i. Continuous Discharge: 12.5 A
ii. Charge: 2 A (standard)
iii. Nominal Ah per cell: 6 Ah
iv. Nominal Voltage per cell: 3.6 V
v. Min/Max Voltage per cell: 2.5 V / 4.2 V
vi. Energy per cell:
1. 6 Ah * 3.6 V = 21.6 Wh
vii. Dimensions per cell: 21.6mm by 71 mm
viii. Weight per cell: 74g

d. Iteration #4
i. Same as iteration #3

e. Iteration #5
i. Same as #4

13) Given the configuration you chose, what is the total energy within the pack? What is the total Ah capacity of the pack? What is the minimum, nominal, and maximum voltage? (3 points)

a. Iteration #1
i. Configuration – 16s125p
ii. Total Cells – 2000
iii. Total Energy:
1. $434.02\ Wh * \frac{57.6\ V}{pack} = 24999.5\ Wh\ or\ \mathbf{25\ kWh}$
iv. Total Ah Capacity:
1. 3.45 Ah * 125 = 431.25 Ah
v. Minimum Voltage:
1. 2.5 V * 16 = 40 V
vi. Maximum Voltage:
1. 4.2 V * 16 = 67.2 V
vii. Nominal Voltage:
1. 3.6 V * 16 = 57.6 V

b. Iteration #2
i. Configuration – 24s64p
ii. Total Cells – 1536
iii. Total Energy:
1. $289.35\ Ah * \frac{86.4\ V}{pack} = 24999.84\ Wh\ or\ \mathbf{25\ kWh}$
iv. Total Ah Capacity:
1. 4.50 Ah * 64 = 288 Ah
v. Minimum Voltage:
1. 2.5 V * 24 = 60 V
vi. Maximum Voltage:
1. 4.2 V * 24 = 100.8 V
vii. Nominal Voltage:
1. 3.6 V * 24 = 86.4 V

c. Iteration #3
i. Configuration – 24s48p
ii. Total Cells – 1152
iii. Total Energy:
1. $289.35\ Ah * \frac{86.4\ V}{pack} = 24999.84\ Wh\ or\ \mathbf{25\ kWh}$

iv. Total Ah Capacity:
   1. 6 Ah * 48 = 288 Ah
v. Minimum Voltage:
   1. 2.5 V * 24 = 60 V
vi. Maximum Voltage:
   1. 4.2 V * 24 = 100.8 V
vii. Nominal Voltage:
   1. 3.6 V * 24 = 86.4 V

d. Iteration #4
   i. Configuration – 30s31p
   ii. Total Cells – 930
   iii. Total Energy:
      1. $185.185\ Ah * \frac{108\ V}{pack} = 19999.98\ Wh\ or\ \mathbf{20\ kWh}$
   iv. Total Ah Capacity:
      1. 6 Ah * 31 = 186 Ah
   v. Minimum Voltage:
      1. 2.5 V * 30 = 75 V
   vi. Maximum Voltage:
      1. 4.2 V * 30 = 126 V
   vii. Nominal Voltage:
      1. 3.6 V * 30 = 108 V
e. Iteration #5
   i. Configuration – 30s35p
   ii. Total Cells – 1050
   iii. Total Energy:
      1. $203.7\ Ah * \frac{108\ V}{pack} = \mathbf{22\ kWh}$
   iv. Total Ah Capacity:
      1. 6 Ah * 34 = 204 Ah
   v. Minimum Voltage:
      1. 2.5 V * 30 = 75 V
   vi. Maximum Voltage:
      1. 4.2 V * 30 = 126 V
   vii. Nominal Voltage:
      1. 3.6 V * 30 = 108 V

14) Given the configuration you chose, what is the maximum continuous discharge current of your pack? What is the peak discharge current? What is the max charge current? Some cell data sheets may only give continuous current and not peak current, ignore peak if that is the case. (3 points)

a. Iteration #1
   i. Maximum Continuous Discharge Current:
      1. 125 * 10 = 1250 A
   ii. Peak Discharge Current:
      1. Datasheet does not provide
   iii. Max Charge Current:
      1. 125 * 1.675 = 209.375 A
b. Iteration #2
   i. Maximum Continuous Discharge Current:
      1. 64 * 45 = 2880 A
   ii. Peak Discharge Current:
      1. Datasheet does not provide
   iii. Max Charge Current:
      1. 64 * 4.5 =288 A
c. Iteration #3
   i. Maximum Continuous Discharge Current:
      1. 48 * 12.5 = 600 A
   ii. Peak Discharge Current:

1. Datasheet does not provide

iii. Max Charge Current:

1. 48 * 2 =96 A

d. Iteration #4
    i. Maximum Continuous Discharge Current:
        1. 31 * 12.5 = 387.5 A
    ii. Peak Discharge Current:
        1. Datasheet does not provide
    iii. Max Charge Current:
        1. 31 * 2 = 62 A
e. Iteration #5
    i. Maximum Continuous Discharge Current:
        1. 34 * 12.5 = 425 A
    ii. Peak Discharge Current:
        1. Datasheet does not provide
    iii. Max Charge Current:
        1. 34 * 2 = 68 A

15) What is the continuous and peak power that your battery pack can produce? (2 points)

a. Iteration #1
    i. P = IV
    ii. Continuous Power Calcs:
        1. 1250 A * 57.6 V = 72 kW
    iii. Peak Power Calcs:
        1. N/A since peak current not given on data sheet
b. Iteration #2
    i. P = IV
    ii. Continuous Power Calcs:
        1. 2880A * 86.4 V = 248.832 kW
    iii. Peak Power Calcs:
        1. N/A since peak current not given on data sheet
c. Iteration #3
    i. P = IV
    ii. Continuous Power Calcs:
        1. 600A * 86.4 V = 51.840 kW
    iii. Peak Power Calcs:
        1. N/A since peak current not given on data sheet
d. Iteration #4
    i. P = IV
    ii. Continuous Power Calcs:
        1. 387.5 A * 108 V = 41.850 kW
    iii. Peak Power Calcs:
        1. N/A since peak current not given on data sheet
e. Iteration #5
    i. P = IV
    ii. Continuous Power Calcs:
        1. 425 A * 108 V = 45.9 kW
    iii. Peak Power Calcs:
        1. N/A since peak current not given on data sheet

16) Given your answers above, what C rates can your pack produce? (continuous discharge, peak discharge, and charge C rates). (2 points)

a. Iteration #1
    i. Continuous Discharge
        1. $1250\ A / 431.25\ Ah = 2.898\ C$
    ii. Peak Discharge
        1. N/A since peak current not given on data sheet

iii. Charge
1. $209.375\ A/431.25\ Ah = 0.4855\ C$

b. Iteration #3
i. Continuous Discharge
1. $2880\ A/288\ Ah = 10\ C$

ii. Peak Discharge
1. N/A since peak current not given on data sheet

iii. Charge
1. $288\ A/288\ Ah = 1\ C$

c. Iteration #3
i. Continuous Discharge
1. $600\ A/288\ Ah = 2.08\ C$

ii. Peak Discharge
1. N/A since peak current not given on data sheet

iii. Charge
1. $96\ A/288\ Ah = 0.333\ C$

d. Iteration #4
i. Continuous Discharge
1. $387.5\ A/186\ Ah = 2.08\ C$

ii. Peak Discharge
1. N/A since peak current not given on data sheet

iii. Charge
1. $62\ A/186\ Ah = 0.333\ C$

e. Iteration #5
i. Continuous Discharge
1. $425\ A/204\ Ah = 2.083\ C$

ii. Peak Discharge
1. N/A since peak current not given on data sheet

iii. Charge
1. $68\ A/204\ Ah = 0.333\ C$

17) Does your battery pack meet the race rules for power and energy? (1 point)

a. Iteration #1
i. Energy on board
1. Allowed: 25 kWh
2. On Car: 25 kWh
3. Verdict: Passes

ii. Power
1. Allowed: 50 kW
2. On Car: 72 kW
3. Verdict: Too much power, breaks the rules

iii. Volts
1. Allowed: 200 V
2. On Car: 57.6 V (nominal)
3. Verdict: There is for sure more room to play here

b. Iteration #2
i. Energy on board
1. Allowed: 25 kWh
2. On Car: 25 kWh
3. Verdict: Passes

ii. Power
1. Allowed: 50 kW
2. On Car: 248.832 kW
3. Verdict: Way too much power, breaks the rules

iii. Volts
1. Allowed: 200 V
2. On Car: 100.8 V (max)
3. Verdict: There is for sure more room to play here

c. Iteration #3
   i. Energy on board
      1. Allowed: 25 kWh
      2. On Car: 25 kWh
      3. Verdict: Passes
   ii. Power
      1. Allowed: 50 kW
      2. On Car: 51.840 kW
      3. Verdict: Slightly over the allowable limit
   iii. Volts
      1. Allowed: 200 V
      2. On Car: 100.8 V (max)
      3. Verdict: There is for sure more room to play here
d. Iteration #4
   i. Energy on board
      1. Allowed: 25 kWh
      2. On Car: 20 kWh
      3. Verdict: Passes
   ii. Power
      1. Allowed: 50 kW
      2. On Car: 41.850 kW
      3. Verdict: Under allowable limit and is rules compliant
   iii. Volts
      1. Allowed: 200 V
      2. On Car: 126 V (max)
      3. Verdict: There is for sure more room to play here
e. Iteration #5
   i. Energy on board
      1. Allowed: 25 kWh
      2. On Car: 22 kWh
      3. Verdict: Passes
   ii. Power
      1. Allowed: 50 kW
      2. On Car: 45.9 kW
      3. Verdict: Under allowable limit and is rules compliant
   iii. Volts
      1. Allowed: 200 V
      2. On Car: 126 V (max)
      3. Verdict: There is for sure more room to play here, but more limited by motor controller choice than rules limit itself

18) What is the <u>total</u> weight of the battery pack? Include the weight of packaging the cells into a pack. Does the weight of your pack satisfy the race rules? (2 points)

a. Iteration #1
   i. Total Weight:
      1. 46.5 g * 2000 = 93,000 g or 93 kg
      2. Covering packaging and enclosure: 93 * 1.5 = **139.5 kg**
   ii. Rules
      1. Allowed: 250 lbs
      2. On Car: 139.5 kg = 307.545 lbs
      3. Verdict: Too high, breaks rules
b. Iteration #2
   i. Total Weight:

            1. 70 g * 1536 = 107,520 g or 107.52 kg
            2. Covering packaging and enclosure: 107.52 * 1.5 = **161.28 kg**
        ii. Rules
            1. Allowed: 250 lbs
            2. On Car: 139.5 kg = 355.561 lbs
            3. Verdict: Too high, breaks rules
    c. Iteration #3
        i. Total Weight:
            1. 74 g * 1152 = 85,248 g or 85.248 kg
            2. Covering packaging and enclosure: 85.248 * 1.5 = **126.372 kg**
        ii. Rules
            1. Allowed: 250 lbs
            2. On Car: 126.372 kg = 278.60 lbs
            3. Verdict: Too high, breaks rules, but is much closer compared to the second iteration
    d. Iteration #4
        i. Total Weight:
            1. 74 g * 930 = 68,820 g or 68.82 kg
            2. Covering packaging and enclosure: 68.82 * 1.5 = **103.23kg**
        ii. Rules
            1. Allowed: 250 lbs
            2. On Car: 103.23 kg = 227.583 lbs
            3. Verdict: Rules compliant
    e. Iteration #5
        i. Total Weight:
            1. 74 g * 1020 = 75480 g or 75.48 kg
            2. Covering packaging and enclosure: 75.48 * 1.5 = **113.22kg**
        ii. Rules
            1. Allowed: 250 lbs
            2. On Car: 113.22 kg = 249.61 lbs
            3. Verdict: Rules compliant

19) Is your design ideal? Is it too energy dense or too power dense? Does your design balance power and energy for the application? Please explain why or why not. **If your design is not ideal, please iterate through the questions again with a new design.** (6 points).
    a. Iteration #1:
        i. No, the design is not ideal. While it does account for 30% extra energy to account for voltage sag, it breaks all rules (except for energy limit on board and voltage). This is not a rules compliant design
        ii. It is relatively power dense since there is too much power outputted
        iii. The design does not balance the power and energy for the application. There is just enough energy on board but it outputs too much power, so not okay. There are less Ah going to each cell, which means that more cells are being used than is otherwise necessary.
        iv. 2000 cells also means that the kart weighs a lot more than it should be, even if you ignore the fact that it is not rules compliant.
    b. Iteration #2:
        i. No, the design is still not ideal. It doesn't improve much on the old design.
        ii. This version is very power dense, as there is way too much power outputted
        iii. The design does not balance power and energy effectively. There is too much power and there is just enough energy.
        iv. The only improvements that occurred was reducing number of cells, but that led to an increase in battery weight due to the cells themselves being almost twice as heavy.
        v. One place to optimize from here is to adjust the number of battery packs required, since that sits at 2.184 before any rounding up.
        vi. Another place to optimize might be to revisit the Wh per lap, since yellow flags and periods of battery management is expected to occur during the race.

c. Iteration #3
    i. While the design has seen a lot of improvements, it is still not 100% perfect.
    ii. Rules compliance:
        1. Battery weight → Not compliant
        2. Power → Not compliant (but very close to being compliant)
        3. Energy on board → compliant
        4. Voltage → Compliant
    iii. All of the non-compliant items are ones that can be fixed with some minor adjustments
    iv. This is a configuration that is more energy dense than power dense, since there is sufficient energy on board and the cells that are used to make up the battery pack have a higher capacity compared to other similar spec batteries
    v. This design is also better since it only allows for 1 pit stop to change batteries in, which reduces time, while also being lighter (but still not light enough)
    vi. This design is able to better balance the power to energy requirements, but slightly biases the energy side of that while being slightly too powerful
    vii. How to fix this for the next iteration?
        1. Reduce the number of cells that run in parallel (can increase the number of series cells since there is room to play)
        2. Find a lighter battery if possible (to reduce weight) or reduce the number of kWh on board to lighten the kart up a bit
        3. Realized during iteration #3, but the motor has to be changed to accommodate higher power requirements

d. Iteration #4
    i. This design is now rules compliant
    ii. There is a significant improvement, with room to improve on it
    iii. This configuration is more energy dense than power dense, as it has the capacity for the kart and the race, but it is a design that could use a bit more power given that there is room to play in that regard

e. Iteration #5
    i. While this design is rules compliant, it is not 100% ideal. Compared to the last iteration, there is more power and a higher capacity on board, however, it now requires barely over 2 packs which does necessitate a third battery. What this does mean also is that the car can be run at higher than 250 Wh per lap since the third pack is not really used as much. This costs extra. It does improve on the car from the last iteration on most metrics. Below is a list that compares items between the last iteration and this one:
        1. Battery Weight → Increased
            a. This increased weight may have a benefit, since if the battery placement can be perfected, it may lead to a benefit with regards to center of gravity, improving cornering
            b. The increased weight does also mean that there will be a lower top speed
        2. Power → Increased
            a. Increased from the last iteration, which may negate any top speed considerations that I had made in the above bullet point
        3. Energy on Board → Increased
            a. Increased means a higher capacity on board, increased time on track before pit stop is required
        4. Voltage → Same/No Change
    ii. I believe that this design is the most balanced of the bunch when it comes to balancing power to energy, in that on paper it is equally energy dense and power dense
        1. That being said, I believe the biggest problem with this is the need for a third battery pack, which is not a huge issue since the number of stops is not a rules requirement, but rather a performance gain if it can be minimized
    iii. For the application, it does balance energy and power for the reasons I have discussed above.
    iv. What would I do with another iteration?

1. I would probably work to find a different battery, possibly one that is lighter and of a similar capacity and discharge rate to keep performance at the similar point that it is.

v. If this car were actually built, I would look into the energy consumption per lap with actual data in mind to see if the 250 is a great estimate or not. To me, it remains an estimate, and I would design with more green flag than yellow flag running.