AuE 881 - Automotive Systems: An Integrated Overview
Final Group Project: Designing a Battery-Electric Vehicle

Due Friday December 11, 2020 at 11:55PM EST

Group project: Work with the team members assigned to your team on Canvas.

Suggested Schedule: To help keep you on track, and to give us an opportunity to provide you some early feedback in class, we suggest you complete each task by the following date:

- Task 1 by Wednesday November 25
- Task 2 by Wednesday December 2
- Task 3 by Monday December 7

Purpose:

(1) To practice model-based systems design
(2) To gain a deeper understanding of the tradeoffs between vehicle subsystems
(3) To learn about model-based design and how to validate requirements using simulations
(4) To learn about subsystem coupling and how it affects the systems design process

Collaboration Policy:

This is a group assignment. It is important that you work closely with your team members on this final project. While it is okay to discuss with your friends from other teams how best to approach the problem, it is completely unacceptable to solve the problem together with other teams, or to copy any portion of the assignment (from another team or from other sources, including the internet). The work your team submits must represent your team's work only.

We already encountered incidents of unauthorized collaboration in the past. The students involved received a grade penalty and the incident was reported to the Department Chair and the Associate Dean of the Graduate School. Let's not allow this to happen again.

Note that we will be using the TurnItIn tool (https://www.turnitin.com) on Canvas to check automatically for plagiarism and copying from peers and from the web.

Description:

In this assignment, your team will "design" an entire battery-electric vehicle! It brings together much of the material covered throughout the entire semester. Given some system-level requirements, you will be asked to make design choices about six different subsystems and/or perspectives: body-in-white, packaging, vehicle dynamics, powertrain, human factors, and systems integration. The overarching goal is to satisfy all the system-level requirements and ultimately, to maximize the profit for your company.

You probably recognized that the list of six subsystems/perspectives corresponds to the different modules covered throughout the semester. To solve the problem, you will need to build on the knowledge you have gained this semester. Specifically, you will need to incorporate the work you have done during some of the previous homework assignments, with some small extensions or modifications. (Note: to have every team start on a level playing field, it is acceptable to build on the homework solutions we provided. Doing so will not be considered plagiarism.)

Like assignments 3, 4 and 5, you will be using MATLAB and Simulink. We encourage you to implement as many of the design equations as possible in these tools so that you can iterate and explore the design space with minimal (human) designer intervention. Without developing this computational support, it will be very difficult to find solutions that satisfy all the requirements.

What is most important in this assignment is not the solution itself, but the solution approach: How did you model the individual requirements and objectives? How did you combine them? In what order did you use each of the models? And, if applicable, how did you iterate through the problem to explore the system-level tradeoffs?

We recognize that the problem we are asking you to solve is quite extensive, to the point where we don't really know the "solution" ourselves. The idea is that the project reflects a real-world conceptual design effort (at a small scale). While we expect that most of the information you need to solve the problem is included in this assignment, it is likely that you will need to make additional assumptions and/or will need to disregard some irrelevant information. If you do make additional assumptions, please, list them clearly in your report.

Report:

The main deliverable is a report. Make sure the report is easy to read and grade. A brief report that clearly communicates all the relevant information is ideal. It is best to structure your report by task (see below) and include all the specific information requested for each task. Include figures as appropriate to make your work process and the corresponding results easy to understand. Note that we may not open your MATLAB and Simulink models — if the information is not included in your report, it may not be considered. Therefore, make sure you *include in your report all MATLAB function and scripts, as well as screenshots of all your Simulink models, including all subsystems.*

Task 1: Get oriented and get organized

In this assignment, you will use a model-based approach to solve your design problem. This means that for the objective, you will need to formulate a model that allows you to compute the value of the objective as a function of the design variables. Similarly, for each of the requirements, you will need to formulate a model that allows you to evaluate whether the requirement is satisfied.

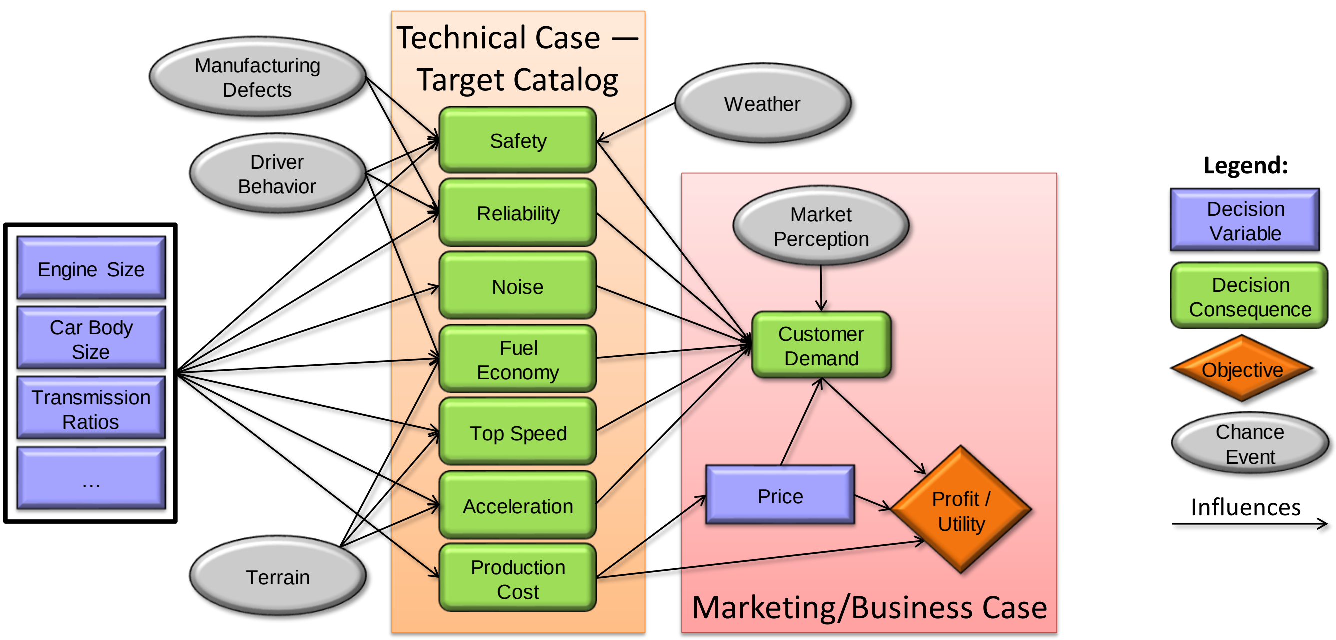
In this first task, start by looking over the appendix in which the design problem is defined, and answer the following questions:

- *What is the objective?* In this case, we adopt a value-driven design perspective with as the objective to maximize profit for the enterprise.
- *What are the vehicle measures of performance?* For each of the perspectives, there are one or more system-level measures of performance, such as ride frequency, top speed, etc. For some of the performance measures, we have imposed requirements (i.e., targets that need to be met). Other performance measures are considered by potential customers and therefore influence demand and profit. We have provided a MATLAB function that relates the following three customer performance measures to profit: 0-

100km/h acceleration time, range on one battery charge, and top speed. A fourth input is cost, which is used by the model to determine the sales price that maximizes profit.

- *What are the design variables?* Design variables are variables that can be independently chosen by the designer. For some design variables, a discrete set of options is available (e.g., we provided three electric motors from which you can choose), while for others, any value (possibly within a given range) can be selected.
- *What are the intermediate variables?* These are variables that are computed only as intermediate results needed to compute a performance measure or another intermediate variable.
- *What are the parameters?* These are "variables" that have a fixed value in the context of your design problem, either because they are constants (e.g., the gravitational acceleration), are externally imposed (e.g., the cost of a component), are assumed to have been determined by other designers (e.g., the drag coefficient is the result of choices made by the exterior designer), or are assumed constant to simplify the problem (e.g., the rolling resistance coefficient depends on the choice of tire, but is assumed to be constant for this problem).

All these variables together can be organized in a network where each node is a variable, and an arrow points from variable A to B if A influences B (i.e., if you need to know A in order to compute B). We encountered an example of such a network in one of the first classes of the semester.



The network can be used to determine the order in which the models need to be solved. Given that the arrows point from left to right in the network above, the order of computation would also move from left to right, so that starting from chosen design variables, we can verify all requirements and compute the resulting objective (i.e., profit, all the way on the right in the graph).

As pointed out before, it is likely that some of the parameters are missing or that some of the provided parameters are not relevant. Ignore the irrelevant parameters, and make a suitable assumption for the missing parameters. You should include the assumptions you make in your final report.

Tasks to be completed by Wednesday November 25th:

1. Create a list of objectives, performance measures, design variables, intermediate variables, and parameters that you expect will need to be considered to solve the constrained optimization problem.
2. Determine for each variable how it will be computed — on which inputs does it depend and how (i.e., using which model) will it be computed from these inputs? Provide a brief description of each model, what the input variables are, and which assumptions will be considered.

In your report:

1. Include the results of the two tasks listed above.
2. Determine the ordering in which these variables can be computed such that all the inputs for each of the models are available (i.e., were given or have been previously computed). In the determination of the order, assume the design variable to be given/chosen. By going through the models as specified, you will then evaluate whether each of the requirements is satisfied (yes/no) and what the value is for the objective. You do not need to consider the process for finding good/optimal values for the design variables.

Task 2: Create the models to evaluate each of the requirements and objective

For each of the variables identified in Task 1, develop a model for how it will computed. For parameters, specify the value you will use (indicating whether the value was given or is assumed). To make sure your model implementation is correct, provide one or more test-cases you have used to verify your model.

Many of the requirements can be modeled using simple algebraic equations. To compute the range on a single charge, 0-100km/h acceleration time, and slope requirements you need to create a Simulink model that can calculate these performance parameters depending on the inputs. You are encouraged to build upon the solutions we have provided you for the previous assignments to find these performance parameters.

Note that for the analysis of the range (i.e., distance on a single battery charge), you will need to consider the efficiency of the electric motor. We have provided data for the efficiency of different motors as .mat files. Use this data to build on the solution provided for HW5 to find the range through Simulink.

Task to be completed by Wednesday December 2nd:

1. Develop a plan for the implementation of each model. Consider how will you approach the model and how you will test each model.

In your report:

1. Include the results of the task listed above.
2. Describe each of the models. Include the MATLAB/Simulink code/screenshot of your scripts/models (and make sure the images are clear and have descriptions).

3. Describe each test-case and include the results (if possible/appropriate in a graph). Describe how the results show your models are functioning as expected.

Task 3: Explore the design space to find a feasible solution

The goal is the play around with the values for the design variables in order to arrive at a design that meets all the requirements.

The goal of this exploration task is two-fold:

1. To build up your experience in vehicle systems thinking: What will be the system-level consequences if we were to increase or decrease the value of a particular design variable?
2. To build up your experience in vehicle systems engineering processes: In which order and how should we take the different requirements and design choices into account?

Rather than modifying the values for the design parameters randomly, you should look for patterns where for some of the design variables, the "optimal value" appears at one of the boundaries (e.g., boundaries as specified by the ranges for typical/acceptable packaging parameters). You can then "compute" the value of the design variable as an algebraic constraint.

Similarly, while some design considerations may be strongly coupled, others may be rather independent and could therefore be postponed until after the iterations over the strongly coupled considerations have converged.

Tasks to be completed by Monday December 7th:

1. Determine a feasible (but not yet optimized) design. The description should consist of both the specified values for all the design variables, and your analyses in terms of corresponding performance measures, including profit.
2. Create a 2D sideview of your vehicle frame that illustrates the passengers, the selected components and layout requirements (i.e. vision cone, ground clearance and angle of approach/departure).

In your report:

1. Include the results of the two tasks listed above.
2. Describe the (partially computational) process you have used to explore the find a feasible solution.
3. Describe the process you have used to improve on or optimize the feasible solution you started with. Use results from different design variable choices (i.e. motor selections, battery capacity, final drive ratio, etc.) to justify the feasible solution you selected.
4. Include the final (optimized) design you have obtained.

<u>Submissions:</u>

- Due Friday December 11, 2020 at 11:55PM EST
- We changed the naming convention of the files to make it easier to grade. **MAKE SURE TO USE THE CORRECT FILE NAMES!**
- On Canvas, submit an electronic copy of your report in pdf format using the following filename AuE881.FinalProject.Group.GroupNumber.pdf (with GroupNumber referring to your group number on Canvas)

- Using the following Google form, also submit a zip file containing all the MATLAB and Simulink files — everything necessary to run your code: https://tinyurl.com/AuE881HW (Only one person per group needs to submit)
- Late submissions are not accepted — 0 points will be earned if you do not submit by the deadline. Hint: don't wait until the last minute to submit!

Academic Integrity

"As members of the Clemson University community, we have inherited Thomas Green Clemson's vision of this institution as a 'high seminary of learning.' Fundamental to this vision is a mutual commitment to truthfulness, honor, and responsibility, without which we cannot earn the trust and respect of others. Furthermore, we recognize that academic dishonesty detracts from the value of a Clemson degree. Therefore, we shall not tolerate lying, cheating, or stealing in any form. For additional information regarding academic integrity, see https://www.clemson.edu/graduate/files/pdfs/gs_policy_handbook.pdf (page 16-26)

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APPENDIX A: Design problem

Design a battery-electric vehicle that maximizes profit for the enterprise and satisfies the requirements listed below. Only the details of the design as characterized by the list of design variables below need to be specified. Please include the values for these design variables for the feasible alternative(s) that you consider for your final report.

List of design variables

- Battery capacity in [kWh]
- Choice of electric motor & inverter pair: A, B, or C (see below for motor characteristics)
- Motor and driveline configuration: FWD 1 motor, FWD 2 motors, RWD 1 motor, RWD 2 motors, AWD 2 motors, AWD 4 motors
- Final drive ratio
- 2-D vehicle layout (multiple dimensions as needed) including, L104 in [mm], L105 in [mm], L108 in [mm], H101 in [mm], H5-1 in [mm], H5-2 in [mm]
- Frame rail: height in [mm], width in [mm], and thickness in [mm]
- Suspension spring constant in [N/m]
- Suspension damping coefficient in [Ns/m]

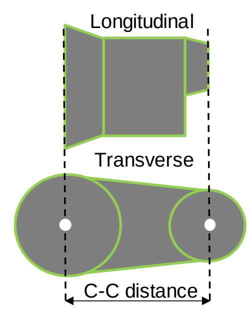
List of requirements:

- The vehicle shall be a **medium car**. Any assumptions about the packaging must take the approximate reference dimensions mentioned in the H-point book into account (see Appendix C)
- The wheelbase, L101, shall be 2700mm (this is an artificial constraint we have imposed purely to simplify the problem).
- For the relevant packaging requirements, refer to the ranges specified as best practices in the lecture notes. This includes limits on ground lines, vision cone, head clearance, ball of foot distance, etc.
- The batteries shall be no closer than 100mm to any passenger.
- In side-view projection, passengers shall not overlap the motor(s) or transmission(s) (but ARE allowed to overlap with the driveline).
- In side-view projection, the batteries cannot overlap with the frame rail (i.e., the batteries cannot be mounted in between the frame rails).
- The vehicle shall accommodate four AM95 passengers (including the driver).
- The vehicle shall accommodate a cargo volume of 0.30 m^3 and 28 kg (7kg/passenger)
- The vehicle shall be able to ascend a 12% slope at 30 km/h.
- The material stress in the frame rail shall be less than 215 MPa under normal loading conditions.
- The maximum deflection of the frame rail shall be less than 15mm.
- The vehicle shall be able to turn on a 100m diameter skidpad at up to 0.8g lateral acceleration
- To avoid the motors and inverters from burning out, the vehicle shall not exceed continuous torque limits indicated in the motor efficiency maps. We assume that continuous torque limits are at 70% of peak torque.

- Assuming the damping is at 30% of critical damping, the ride frequency (the resonant frequency) shall be equal to 1.2 Hz in the front and 1.44 Hz in the rear. *Hint: These requirements depend on the weight and weight distribution of the vehicle.*
- The vision cone for the driver extends no less than 6 deg down and 15 deg up relative to horizontal.
- The ground clearance of a fully rated vehicle (at GVWR) shall be no less than 130 mm.
- The angle of approach shall be no less than 12 deg.
- The angle of departure shall be no less than 12 deg.
- The ramp breakover angle shall be no less than 10 deg.
- The center of gravity should fall between 45 to 55 percent of the wheelbase measured from the front wheel axle along the vehicle length

List of volumes that need to be packaged
(length x height — 2D layout is considered. CG is assumed in middle of volume)

- Passengers (2 rows of 2)
- Misc. Electronics: negligible (0m x 0m)
- Wheel Assemblies: bounded by wheel diameter
- Gearbox (single-speed):
  - 0.25m x 0.4m for low-torque gearbox (torque<300Nm continuous)
  - 0.3m x 0.5m for high-torque gearbox (torque>300Nm continuous)
- Differential:
  - 0.24m x 0.24 if separate
  - 0m x 0m if on same axle and integrated into transmission
- Driveline:
  - motor-gearbox connection can be transverse/longitudinal
  - Two motors may be coupled to a single gearbox (doubles the torque)
  - Center-center distance between input and output flanges of gearbox is fixed to 250mm



- Frame rail (as per your design — runs the length of the car)
- Battery: 600Wh/liter (max battery width: 1250mm)
- Prop shaft: 0.075m x designed length
- Motor + Inverter (see below for motor and inverter information)

List of masses that make up the total vehicle mass:

- 4 AM95 passengers (101kg/passenger)
- Cargo per EPA (7kg/passenger)
- Infotainment (15kg)
- Sunroof (10kg)
- Unsprung masses (60kg/corner)
- Gearbox (single-ratio):
  - 28kg for low-torque gearbox (torque<300Nm)
  - 45kg for high-torque gearbox (torque>300Nm)
- Differential (10kg)
- Axles (5kg per half shaft)
- Body (Length X height x 50kg/m2)

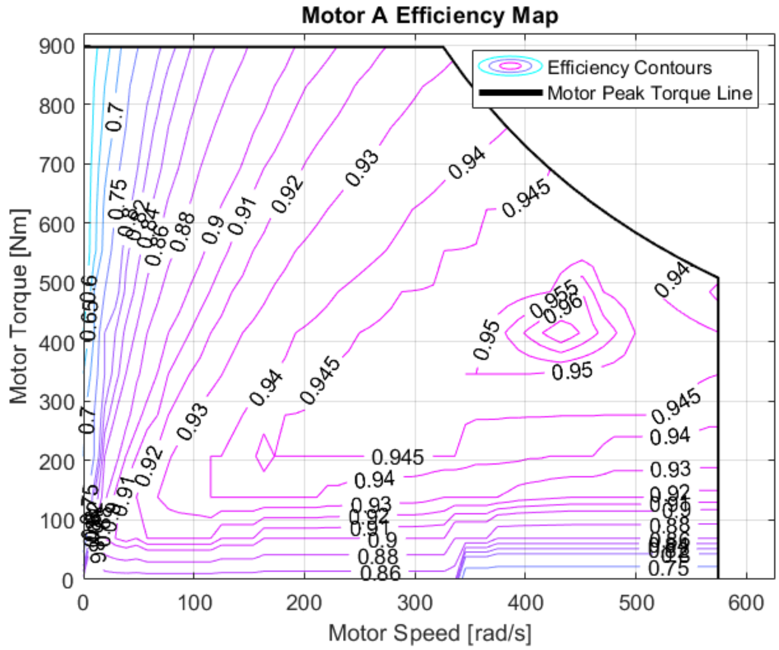
- Frame rail: (to simply account for the cross members, assume the total weight of the frame to be 3 times the weight of the frame rail in the side view) -- Steel: 7800kg/m^3
- If selected, prop shaft (10kg/m)
- Battery (250Wh/kg)
- Motor+Inverter (see below for motor and inverter information)

Costs of components that make up the vehicle:

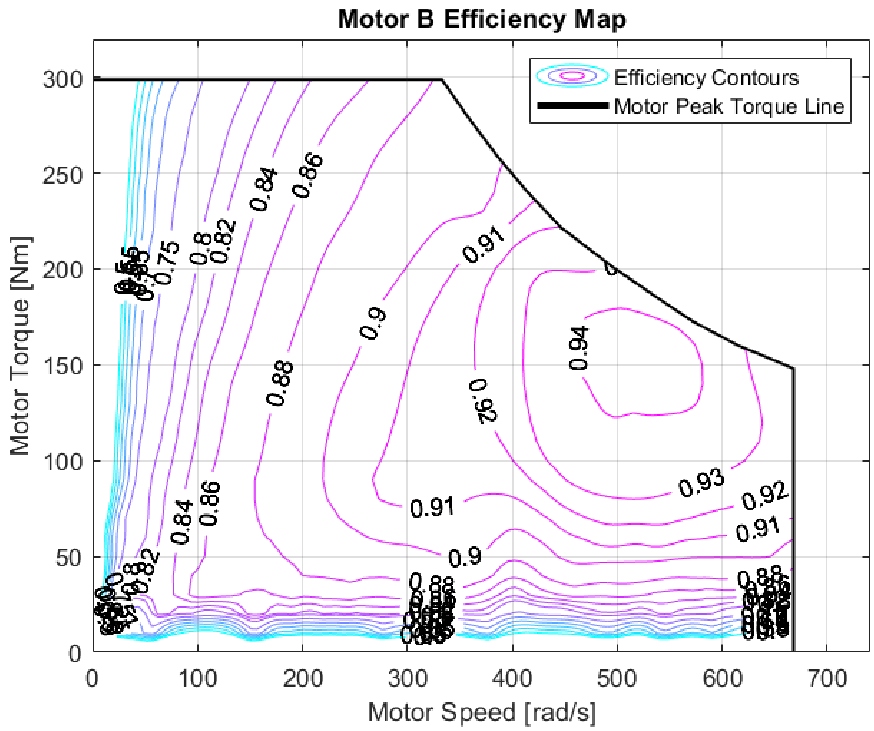
- Misc. Electronics: $3000
- Wheel Assemblies: $450/corner
- Gearbox (single-ratio):
    - $4000 for low-torque gearbox (torque<300Nm)
    - $7500 for high-torque gearbox (torque>300Nm)
- Differential: $600
- Axles: $350
- Motor & Inverter (see below for motor and inverter information)
- Body: cost is proportional to bounding-box volume: 1000$/m^3
- Frame rail: cost is proportional to mass: $2/kg
- Battery: cost is proportional to capacity: $145/kWh
- Prop shaft: cost is proportional to length: $600/m

Motor + inverter characteristics (continuous power is considered at 70% of peak):

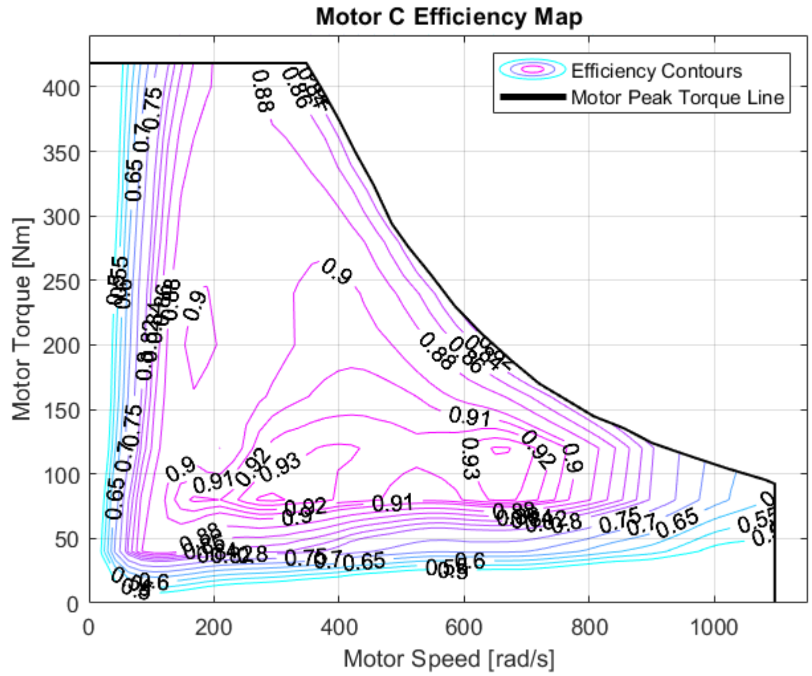
- Motor-Inverter A (UQM PowerPhase HD250)
    - Motor mass: 85 kg
    - Inverter mass: 35 kg
    - Power rating: 175 kW continuous, 250kW peak
    - Motor bounding-box dimensions: cylinder with 0.32m in length and 0.39 in diameter
    - Inverter bounding-box dimensions: 0.531m x .422m x 0.175m (can be mounted in any direction)
    - Cost: $7500
    - Efficiency map: (maximum speed = 5500 rpm)



- Motor-Inverter B (UQM PowerPhase Pro 100)
  - Motor mass: 41 kg
  - Inverter mass: 16 kg
  - Power rating: 70 kW continuous, 100kW peak
  - Motor bounding-box dimensions: cylinder with 0.286m in length and 0.276 in diameter
  - Inverter bounding-box dimensions: 0.418m x .393m x 0.18m (can be mounted in any direction)
  - Cost: $5200
  - Efficiency map: (maximum speed = 6400 rpm)



- Motor-Inverter C (Similar to Remy HVH250)
  - Motor mass: 55 kg
  - Inverter mass: 12 kg
  - Power rating: 100 kW continuous, 143kW peak
  - Motor bounding-box dimensions: cylinder with 0.28m in length and 0.28 in diameter
  - Inverter bounding-box dimensions: 0.434m x .2m x 0.08m (can be mounted in any direction)
  - Cost: $5500
  - Efficiency map: (maximum speed = 10500 rpm)



List of given parameters:

- Gravitational acceleration $g = 9.81\ m/s^2$
- Drag coefficient $C_d = 0.27$
- $W101 = 1550\ mm$
- $W103 = 1820\ mm$
- Tire size = $225/45R18$
- Density of air $\rho = 1.26\ kg/m^3$

Modeling suggestions:

- For the meaning of packaging variables, refer to the H-Point book and the SAE J1100 standard.
- For approximate reference dimensions, see Appendix C as a guideline.
- Approximate the cross-sectional area of the vehicle as: A = W103*H101
- Assume that the CG of an electric motor is located 300mm from the axle it drives. The motor could thus be to either side of the axle, but always at 300mm measured horizontally.
- Assume that the masses of the suspension components are incorporated into the unsprung mass.
- When computing the range, assume that the vehicle will repeatedly follow a US06 drive cycle
- To perform the range prediction, start from the model from HW5 but incorporate the efficiency maps for the motors (see Appendix B).
- Assume that the center of gravity of the BiW is in the middle between front and rear bumpers and at 1/3 (measured from the bottom) between the floor and the roof.

- Assume a simple single mass-spring-damper quarter car model to determine the resonant frequency (note that for damped systems the resonant frequency is different than the natural frequency)
- Assume that the electrical behavior can be adequately approximated using energy flow (without the consideration of voltages and currents).
- Assume the maximum loads on the frame to equal twice the static gravitational loads.
- Assume that the loads are supported by a frame consisting of two rectangular steel tubes with outer dimensions height h, width w, and thickness, t. Each load force is divided equally over the two rails and acts on them at the location of the corresponding center of gravity. The maximum stress occurs where the bending moment is largest.
- To account for cross beams etc., model the mass of the frame to be 3 times the mass of the rails.
- Assume that the length of the frame equals the length of the car.
- Use the provided MATLAB function SFBM.m to calculate the bending moment in the frame rail. This will help you to design your frame rail according to the given (maximum allowable deflection) stiffness requirement. See also Appendix B below.

APPENDIX B: MATLAB support file

On Canvas, you can find the following zip files with MATLAB tools that you can use for this assignment:

- ProfitModel.zip — a function you need to use to predict the profit for your car design (look first at profitTest.m)
- MotorMaps.zip — the data for the efficiency maps of the electric motors (look first at MotorMapExample.m)
- DesignVisualization.zip — some functions to help with the visualization of the layout (look first at BEV_DesignVisualization.m)
- SFBM.zip — a set of tools to solve “Shear Force Bending Moment” problems (look first at testing.m)
- BEV_DriveCycle.zip — a Simulink model and corresponding script to perform a US06 drive cycle

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APPENDIX C: Reference Dimensions

APPROXIMATE REFERENCE DIMENSIONS

The table below contains some examples of dimensions taken from current production cars. Use these to set up an initial package, assuming that the criteria that has driven these numbers is similar to your concept. As the design develops and key elements in the package evolve, these may change.

As you work through the process, develop an understanding of the factors that govern these interior environment dimensions.

		DRIVER & FRONT PASSENGER										REAR OCCUPANTS						
		Heel to Ground (Ref)	Chair Height H30	H point to ground H5	Back Angle A40	Effective Head Room H61	Upward Vision Angle A60	Downw'd Vision Angle A61	Shoulder Room W3	Hip Room W5	Lateral Location W20	Couple L50	Chair Height H30-2	Back Angle A40-2	Effective Head Room H61-2	Shoulder Room W3-2	Hip Room W5-2	Lateral Location W20-2
CARS	NEV	325	400	725	15.0	1075	11.0	10.0	-	-	275	-	-	-	-	-	-	-
	SPORTS CAR	175	150	325	28.0	950	8.0	5.0	1350	1275	325/400	-	-	-	-	-	-	-
	MICRO CAR	350	275	625	21.0	1000	14.0	11.0	1200	1150	300	-	-	-	-	-	-	-
	SMALL ELECTRIC CAR	450	250	700	24.0	975	15.0	9.0	1325	1325	350	750	275	26.0	950	1325	1325	325
	SMALL CAR	225	250	475	24.0	975	15.0	7.0	1350	1325	350	750	275	27.0	950	1350	1325	325
	MEDIUM CAR	250	250	500	24.0	975	14.0	7.0	1475	1400	350	850	275	27.0	950	1475	1400	325
	MEDIUM COUPE	250	175	425	24.0	950	13.0	5.0	1375	1325	350	750	200	27.0	875	1375	1325	325
	LARGE CAR	275	250	525	24.0	975	14.0	6.0	1500	1450	375	900	275	27.0	975	1500	1450	400
	LARGE LUXURY CAR	275	275	550	22.0	975	15.0	7.0	1550	1500	400	975	300	28.0	975	1550	1450	375
TRUCKS	MINIVAN	425	350	775	20.0	1010	19.0	11.0	1575	1525	425	850	375	22.0	1000	1575	1525	400
	SMALL SUV	400	350	750	22.0	1010	15.0	9.0	1425	1400	400	800	375	24.0	1000	1425	1375	375
	MEDIUM SUV	450	300	750	22.0	1010	14.0	6.0	1500	1450	400	825	325	24.0	1000	1500	1450	425
	LARGE SUV	450	325	775	22.0	1025	14.0	7.0	1650	1600	375	875	350	24.0	1025	1650	1600	375
	SMALL TRUCK	400	300	700	22.0	1010	14.0	7.0	1475	1450	375	625	325	18.0	950	1475	1425	400
	LARGE 4x4 TRUCK	600	350	950	22.0	1025	15.0	8.0	1700	1650	475	950	375	18.0	1025	1700	1650	475
	COMMERCIAL VAN	725	350	1075	22.0	1010	10.0	10.0	1675	1625	525	900	425	19.0	1000	1675	1625	500