Förnyelsebar elproduktion och eltransporter (DAT460)

Hybrid and Electrical Vehicles

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Project description

The aim of this project is that the student will learn how to calculate and analyze the power and energy consumption of vehicles. You will work with the basic vehicle dynamic equations to study the forces that act on a vehicle. Furthermore, you will examine the losses of an electric machine in different operating points by using a datasheet of permanently magnetized DC motors. Finally, you will need to read one article about vehicle batteries and study some concepts about battery modeling.

One Excel file is given to do the vehicle dynamic calculations, and there are four sheets inside:

- Parameters
- Calculation1
- Calculation2
- Plots

Table of contents

1. Vehicle dynamics and energy consumption

During vehicle driving the driver pushes the gas and brake pedals to control the speed and acceleration. Vehicle simulations aim to estimate fuel consumption. Speed and acceleration are instead often regarded as input information. Then, the necessary forces (and power) that come from the drive system to the wheels **(F_{wheel})**, and from friction brake system to the wheels **(F_{brake})**, are calculated based on vehicle dynamics.

There are three external forces that act on a vehicle during driving, **air drag**, **rolling resistance** and **grading (road slope)**. Both the *air drag force* **(F_a)** and the *rolling resistance force* **(F_r)** are always working against the direction of travel, whereas the *grading force* **(F_g)** only works against the direction of travel during uphill driving. During downhill driving, the *grading force* is directed in the same direction as the vehicle travel, thus contributing to the propulsion of the vehicle.

The sum of *air drag*, *rolling resistance* and *grading* are sometimes called the *road load* **($F_{road\ load}$)** and they can individually be estimated accordingly.

- Air drag: $F_a = \frac{1}{2} \cdot \rho_{air} \cdot C_d \cdot A \cdot v^2$
- Rolling resistance: $F_r = C_r \cdot m \cdot g \cdot \cos(\alpha) \approx C_r \cdot m \cdot g$
- Grading: $F_g = m \cdot g \cdot \sin(\alpha)$

Compare: power content in wind from wind power assignment: $P = F * v = \frac{1}{2}\rho_{air} C_p A v^3$

The orange parameters are vehicle specific.

ρ_{air}	(kg/m³)	air density ($1.225 kg/m^3$ at standard atmospheric conditions)
C_d	-	coefficient of aerodynamic resistance, depend on shape of vehicle
A	(m²)	vehicle effective frontal area
v	(m/s)	vehicle speed
C_r	-	rolling resistance coefficient, depend on material, temperature, structure, pressure etc. of both tire and road
α	(rad)	angle of road inclination
m	(kg)	mass of vehicle including passengers and cargo
g	(m/s²)	gravitation constant on earth ($9.81\ m/s^2$)
a	(m/s²)	acceleration of vehicle

According to Newton's second law of mechanics ($\sum F = m \cdot \frac{dv}{dt} = m \cdot a$); if the sum of forces acting on a vehicle is positive then it will accelerate in the direction of the net force, i.e. forward, and if the sum is negative, it will decelerate. The following thus applies:

$$F_{wheel} - F_{road\ load} = m \cdot a = F_{acc}$$

where $\boldsymbol{F_{wheel}}$ is the drive system and/or the brake force ($F_{wheel} = F_{powertrain} - F_{brake}$), and $\boldsymbol{F_{acc}}$ is the resulting acceleration force. In this assignment, only forward driving is considered and the direction of force from the powertrain causing a forward acceleration is defined as positive.

In order to sustain a certain speed and acceleration on a given road slope with a specific vehicle, the force that has to come from the drive system and/or brake system is thus:

$$F_{wheel} = F_a + F_r + F_g + F_{acc}$$

There are three possible net outputs from the drive system and/or brake system to the wheel shaft:

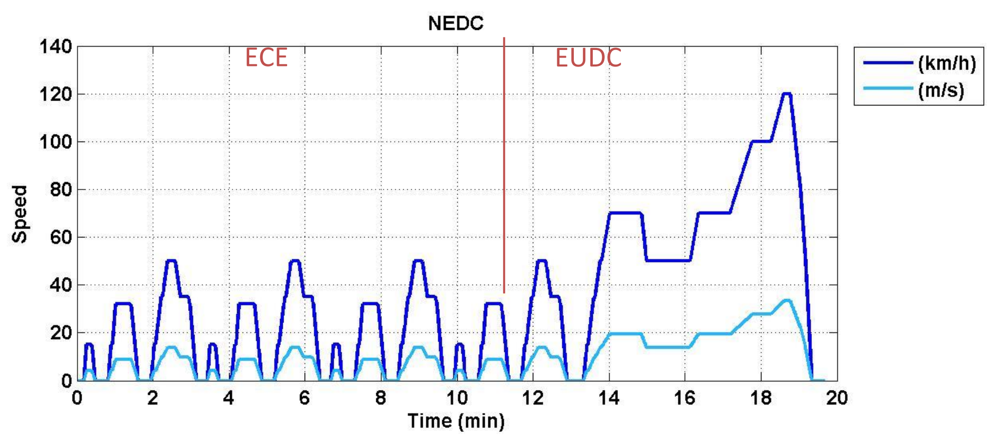
$F_{wheel} > 0$	The drive system is providing a propulsion force, controlled via the gas pedal.
$F_{wheel} < 0$	• Either the **friction brake** system is providing a braking force on the wheels, controlled via the brake pedal, or… • …an **electric machine** is controlled to provide a braking force, or… • …a **combustion engine** is still engaged on the wheel shaft and the internal friction in the engine and gear system provides a braking force (for example due to friction as the piston is forced to move up and down in the cylinder).
$F_{wheel} = 0$	Neither the drive system nor the brake system provides any force to the wheel shaft, i.e. the vehicle is *coasting* while mainly the external frictional forces decelerate the vehicle. This happens when neither the gas nor the brake pedals are pressed, and the engine is disengaged from the wheel shaft via the clutch.

Having an electric drive system thus imposes an alternative method for braking, apart from the conventional friction brake system. The benefit is that the vehicle's kinetic energy can be captured and stored in a buffer such as the electrochemical battery, i.e. so called ***regeneration of braking energy*** *or* ***regenerative braking***.

The necessary power P (W), required from the powertrain to sustain a certain operating point can be calculated by multiplying the wheel force with the wheel speed, or the torque with the angular speed as:

$$P\ (W) = F\ (N) \cdot v\ (m/s) = T\ (Nm) \cdot\ \omega\ (rad/s)$$

When assessing vehicle fuel consumption and emissions in automotive industry, standardized **drive cycles** are used, such as the NEDC cycle in the European Union with its' two parts called ECE and EUDC, see figure below. Drive cycles typically contain a specific speed-time profile which is aimed to represent different driving patterns. The ECE cycle is meant to represent city driving with many starts and stops at relatively low speed. The EUDC cycle represent main road to highway driving, with higher speed and no stop-and-go.



Assume the following values for the vehicle (VW Lupo):

Vehicle	Weight	Cd	A	Cr	Tire radius
Small car	830 kg	0.29	2.00 m^2	0.007	0.2785 m

Task 1

In this task you will get familiar with the base equations of vehicle dynamics and learn how to calculate power and energy consumption. The Excel file will be used for calculation.

Q 1.1

In the Excel file: Calculation1, the NEDC driving cycle is describe in column B and column C. The speed curve (Speed VS Time) of the NEDC driving cycle has been plotted in the Excel file: Plots, Plot1. Mark the ECE and EUDC parts

Next step is to do road load calculation, first assuming the road inclination angle is zero. The zero road inclination angle is shown in the Excel file: Calculation1, column I.

Q 1.2

In the Excel file: Calculation1, use the following equations to calculate the air drag force and rolling resistance force in the column K and column L. The vehicle speed of the NEDC driving cycle shall be used.

$$F_a = \frac{1}{2} \cdot \rho_{air} \cdot C_d \cdot A \cdot v^2$$

$$F_r = C_r \cdot m \cdot g \cdot cos(\alpha)$$

Use the following equation to calculate the grading force in the column M. Since the road inclination angle in this question is zero, the calculated grading force shall also be zero.

$$F_g = m \cdot g \cdot sin(\alpha)$$

Sum up the air drag force, rolling resistance force and the grading force, to calculate the total road load force in column N.

$$F_{road\ load} = F_a + F_r + F_g$$

The curves of air drag force, rolling resistance force and total road load force have been plotted in the Excel file: Plots, Plot2 – Plot5. Give some comments based on these plots.

Now, the road inclination angle shall be considered.

Q 1.3

One example of the road inclination angles is given in the Excel file: Calculation2, column J. The road inclination angle curve (Road inclination angle VS time) is also plotted in the Excel file: Plots, Plot6.

Calculate the new air drag force, rolling resistance force, grading force, and total road load force by considering the new road inclination angles, in the Excel file: Calculation2, column L, column M, column N, and column O.

Curves of new rolling resistance force, new grading force, new total load force have been plotted in the Excel file: Plots, Plot7-Plot9.

How does the influence of grading force compare to the other forces in terms of magnitude?

Next step is to calculate the force on the wheels.

Q 1.4

The acceleration of the NEDC driving cycle shall be calculated in the Excel file: Calculation2, column P. The following equation can be used:

$$a(t) = \frac{v(t+1) - v(t)}{\Delta t}$$

where a(t) is the acceleration at the time t, v(t) is the speed at the time t, Δt is the time step.

In the Excel file: Calculation 2, column Q, calculate acceleration force. The following equation can be used:

$$F_{acc} = m \cdot a$$

In the Excel file: Calculation 2, column R, calculate the force on wheels by using the following equation:

$$F_{wheel} = F_{road\ load} + F_{acc}$$

The acceleration force and the force on the wheels have been plotted in the Excel file: Plot10, Plot11. What are the meanings of the positive and negative wheel force?

As explained before, the vehicle regeneration is to utilize the vehicle kinetic energy and store it in the electrochemical battery. The regeneration process happens when the wheel force is negative. If the vehicle has no regeneration process, the negative wheel force will not be utilized. The vehicle brake system will provide the negative force and convert the kinetic energy into the heat energy.

Q 1.5

In the excel file: Calculation2, column S, calculate the power provided by the vehicle powertrain system if there is no regeneration process. The following equation can be used:

$$P = F_{wheel} \cdot v$$

In the excel file: Calculation2, column T, calculate the power provided by the vehicle powertrain system, as well as the regeneration power to the battery (assuming 100% regeneration).

The curves of the power when there is no regeneration process and when there is regeneration process have been plotted in the Excel file: Plot12, Plot13.

When there is no regeneration process, what is the mean power? What is the maximum power? What is your comment on the difference between the mean and maximum power when doing the powertrain design?

When there is regeneration process, what is the mean power? How much is the difference, compared to when there is no regeneration process.

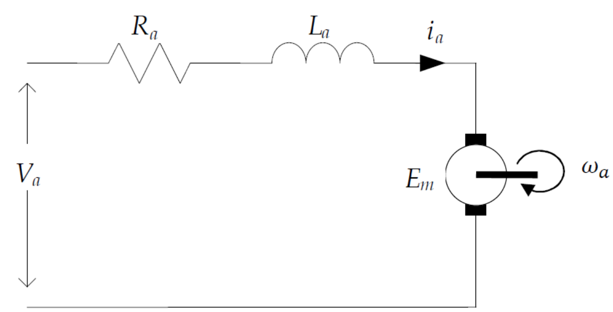
Under which part of the driving cycle (ECE or EUDC) is the regenerative braking most beneficial? Why is that?

2. Electric Machine losses and efficiency

An electric machine converts between electrical and mechanical power. All electric machines are in principle able to work in both directions; that is both as a *motor* and as a *generator*. In **motor mode**, the input is electric power (voltage and current) and the output is mechanical power, i.e. a rotating shaft with a certain torque at a certain speed. The torque and speed operating points depend both on the electrical input and on the load, which could be a fan or a laundry machine or a vehicle. In **generator mode**, the input is instead mechanical power, i.e. something that forces the rotor to rotate with a certain torque at a certain speed, and the output is electrical power. This is the case in a wind or hydro power turbine, or during braking of an electric car.

The simplest machines to study are the dc-machines which operate with dc voltage. For simplicity we will look at a **permanent magnet dc motor**. It´s equivalent electrical circuit model is presented below.

V_a	Armature voltage (V)
i_a	Armature current (A)
R_a	Armature winding resistance (ohm)
L_a	Armature winding inductance (H)
E_m	Induced voltage (back emf) (V)
ω_a	Rotor speed (rad/s)
n_a	Rotor speed (rpm, rotations per minute) $n_a = \omega_a \cdot \frac{60}{2\pi}$



In electrical steady state the inductance can be neglected, thus the relations are as follows;

$$E_m = k_{v\omega}\omega_a$$

$$V_a = R_a i_a + E_m = R_a i_a + k_{v\omega}\omega_a$$

$$T_e = k_{it} i_a$$

where $k_{v\omega}\left[\frac{V}{rad/s}\right]$ and $k_{it}\left[\frac{Nm}{A}\right]$ are electric machine constants that depend on flux density (in this case magnet strength), number of turns of the armature winding etc. T_e [Nm] is the electrodynamical torque.

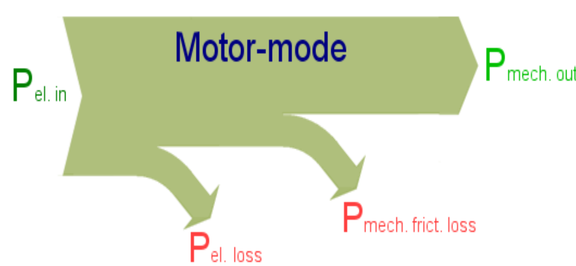
To keep a steady speed, the produced torque must compensate any load torque applied to the shaft. Otherwise, the speed will change. The balancing equation is described as below:

$$J\frac{d\omega_a}{dt} = (T_e - T_{internal\ load}) - T_{external\ load} = T_{shaft} - T_{external\ load}$$

where J [kgm^2] is the rotational inertia of the system, $T_{internal\ load}$ is the internal mechanical losses in the motor mainly due to friction, T_{shaft} is the net output torque on the motor shaft, and finally $T_{external\ load}$ represent the torque required to run the applied load.

When an electric motor operates, a high torque output demands a high current input, and a high speed demands a large applied voltage.

Naturally, power losses are inevitable while converting between electrical and mechanical power. There are both electrical and mechanical losses, as can be seen in the schematic figure in the right.



The **mechanical power losses** are, as stated above, mostly frictional torque losses in the bearings, and are often modeled as a linear or perhaps sometimes a quadratic function of speed;

$$P_{mech\ loss} = T_{frict} \cdot \omega_a.$$

The **electrical power losses** consist of two main parts; ***copper losses*** (also called *conduction losses*, or *joule losses*), ***iron losses*** (also called *core losses* or *magnetic losses)*. The iron losses spring from induced currents and magnetic hysteresis losses, both in iron cores. In this task, the dc motor we study has no iron core, thus no iron losses. The conduction losses are caused by the current through the winding resistance as in

$$P_{el\ loss} = {i_a}^2 \cdot R_a.$$

The efficiency of an electric machine in motor mode is the ratio of the output mechanical power, $P_{mech} = T_{shaft} \cdot \omega_a$ over the electrical input power, $P_{el} = V_a \cdot i_a$.

A motor can be used far outside the nominal operating area for shorter periods of time. The main constraints are maximum allowed thermal heating of the copper winding due to losses, and maximum recommended speed because of wear of mechanical parts such as brushes (if any).

Task 2

In this task you will examine the losses of an electric machine in different operating points. We will look at a 250 W permanently magnetized DC motor with no iron core: Maxon RE65-353296-**36V** (marked in yellow box). Note, in the data sheet the inverse of $k_{v\omega}$ is given.

Motor Data (provisional)			353294	353295	353296	353297	353298	353299	353300	353301
	Values at nominal voltage									
1	Nominal voltage	V	18.0	24.0	36.0	48.0	60.0	70.0	70.0	70.0
2	No load speed	rpm	3350	3880	3770	3480	3490	3260	3020	2550
3	No load current	mA	714	647	407	271	217	170	153	123
4	Nominal speed	rpm	3100	3640	3550	3270	3290	3060	2820	2350
5	Nominal torque (max. continuous torque)	mNm	452	510	654	746	782	819	830	886
6	Nominal current (max. continuous current)	A	10.0	9.62	7.74	6.02	5.04	4.21	3.94	3.54
7	Stall torque	mNm	14700	16800	18600	17100	17200	16000	14500	12900
8	Starting current	A	302	297	208	132	106	78.8	66.3	49.9
9	Max. efficiency	%	81.6	84.3	87.3	88.5	89.1	89.3	89.1	88.9
	Characteristics									
10	Terminal resistance	Ω	0.0596	0.0809	0.173	0.363	0.566	0.888	1.06	1.4
11	Terminal inductance	mH	0.252	0.343	0.848	1.79	2.8	4.38	5.11	7.18
12	Torque constant	mNm / A	48.6	56.7	89.1	130	162	203	219	259
13	Speed constant	rpm / V	196	168	107	73.7	58.9	47.2	43.7	36.8
14	Speed / torque gradient	rpm / mNm	0.241	0.24	0.208	0.206	0.206	0.207	0.211	0.199
15	Mechanical time constant	ms	3.49	3.25	3.0	2.9	2.85	2.83	2.83	2.8
16	Rotor inertia	gcm²	1380	1290	1380	1340	1320	1310	1280	1340

Look at the datasheet supplied and identify the necessary pieces of information in order to do calculation. The friction torque is assumed to be the same within the complete motor speed range in this task.

Q 2.1 Calculate the friction torque, mechanical power losses and electrical power losses under no load conditions. Note: No load speed, no load current, terminal resistance in the data-sheet shall be used.

Q 2.2 If the external load torque on the motor is 10Nm when the rotor is started, calculated the rotor acceleration at the beginning.

Q 2.3 If the rotor speed increases, how will the mechanical power losses change? Explain?

Q 2.4 If the rotor speed increases (armature current unchanged), how will the armature voltage change? Explain?

Q 2.5 If the electrodynamic torque increases, how will the electrical power losses change? Explain?

3. Battery cell modeling

There are many types of batteries on the market, for example Lead-acid, NiCad, NiMH, Lithium-ion, Lithium-polymer etc. In the last decade large steps have been made in battery technology, a development which can be expected to continue.

In conventional cars with combustion engines, the starter battery is usually of Lead–acid technologies. These batteries are heavy per stored unit of energy and power. About a decade ago, NiCad batteries were common in electric vehicles. These batteries can carry more than double the amount of energy for the same weight compared with Lead-acid batteries. A few years later the NiMH batteries became very common. For example, the first models of Toyota Prius HEV were equipped with this type of batteries. Today the leading battery technologies are Li-ion. With these technologies, it is possible to bring more than 5 times the energy compared to the Lead-acid for the same weight. One disadvantage though is the higher cost. Another issue is safety. Despite these issues, today most new commercially available electric vehicles are equipped with Lithium-ion batteries.

When discussing batteries, terms like *Ah*, *C-rate*, *SOC* are often used. The capacity of a battery is often stated in ***Ah*** (Ampere hours). If a battery has a capacity of 5Ah hours, it can deliver 5A for 1 hour. Or it can deliver 1A for 5 hours.

The amount of **energy** the battery can deliver is the current multiplied with the voltage and integrated over time. A complicating factor is that the battery terminal voltage varies depending on the amount of current that is delivered to or drawn from the battery. The internal voltage level also depends on the ***State Of Charge***, ***SOC***, which is a number between 0 and 1 (or 0-100 %) that tells us how much charges are still left in the battery, such that an SOC of 1 (or 100 %) means that the battery is fully charged.

The ***C-rate*** describes how fast we charge or discharge the battery. If we discharge the battery with 1C, we will empty the total battery capacity in 1 hour. If we use 2C, the battery will be emptied in a half hour, and we will then draw a current twice as large as in the 1C case.

The total energy content is the pack voltage times the pack ampere hours. Each battery cell typically holds just a few volts and can deliver only a few ampere hours. Different battery technologies have different typical ratings. A Li-ion cell can have a cell voltage of around 4V, for example. To reach desired battery pack voltage and energy rating, many cells are combined. By series connecting cells the battery voltage can be increased. If the battery pack’s energy content is not enough with one layer of series connected cells, it can be increased by adding one or several parallel layers as well, which increases the pack ampere hours.

Task 3

The article "*A Generic Battery model for the Dynamic Simulation of Hybrid Electric Vehicle*" describes a universal battery model for different types of batteries. Read this article and answer the following questions.

Q 3.1

One battery model is described by equation (1) and (2) in the provided article. These two equations are also shown below:

$$E = E_0 - K \cdot \frac{Q}{Q - \int idt} + Aexp\left(-B \cdot \int idt\right)$$

$$V_{batt} = E - R \cdot i$$

Note: In the above equation, $\int idt$ represent the amount of the capacity which has been used. If the battery is discharged with a constant current, the following equation can be used:

$$\int idt = i \cdot t$$

The model parameters of four different type batteries are shown in the table 1 in the provided article. The table is also given below:

TABLE I
BATTERY PARAMETERS

Type Parameters	Lead-Acid 12V 1.2Ah	Nickel-Cadmium 1.2V 1.3Ah	Lithium--Ion 3.6V 1Ah	Nickel-Metal-Hydrid 1.2V 6.5Ah
$E_0(V)$	12.6463	1.2505	3.7348	1.2848
R (Ω)	0.25	0.023	0.09	0.0046
K (V)	0.33	0.00852	0.00876	0.01875
A (V)	0.66	0.144	0.468	0.144
B $(Ah)^{-1}$	2884.61	5.7692	3.5294	2.3077

Calculate the no-load voltages of the following 4 occasions:

- *Lead-Acid battery, discharged by 0.2A for 2 hours;*
- *Nickel-Cadmium battery, discharged by 1A for 1 hour;*
- *Lithium-Ion battery, discharged by 0.1A for 5 hours;*
- *Nickel-Metal-Hydrid battery, discharged by 2A for 2 hours;*

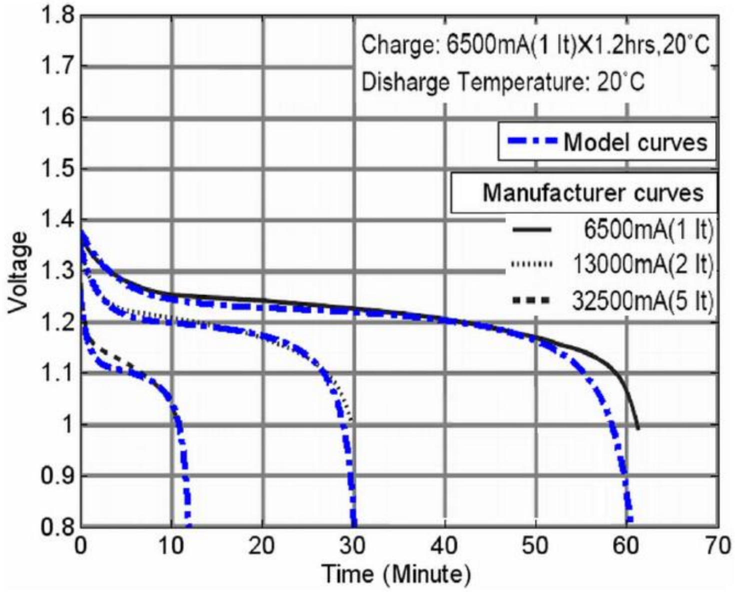
Q 3.2

If the nominal discharging C-rate of one lithium-ion battery is 0.2C. The battery capacity is 3500mAh, and the nominal voltage is 3.6V. The internal resistance is 2mΩ. Using the equation 3 in the given article to calculate the battery efficiency.

$$\eta = 1 - \frac{I_{nom} \cdot R \cdot I_{nom}}{V_{nom} \cdot I_{nom}}$$

Q 3.3

Observe the figure 3 in the given article (which is also shown below). The black curves are from experiments. It can be seen when the discharging current is 6500mA it takes 62 minutes to fully discharge the battery (when V_{batt} equals to 1V). When the discharging current is 13000mA it takes 30 minutes to fully discharge the batter.



Calculate the battery capacity with different discharging currents. Which case gives a bigger capacity? Why?

Hint: Consider the following equation:

$$V_{batt} = E - R \cdot i$$