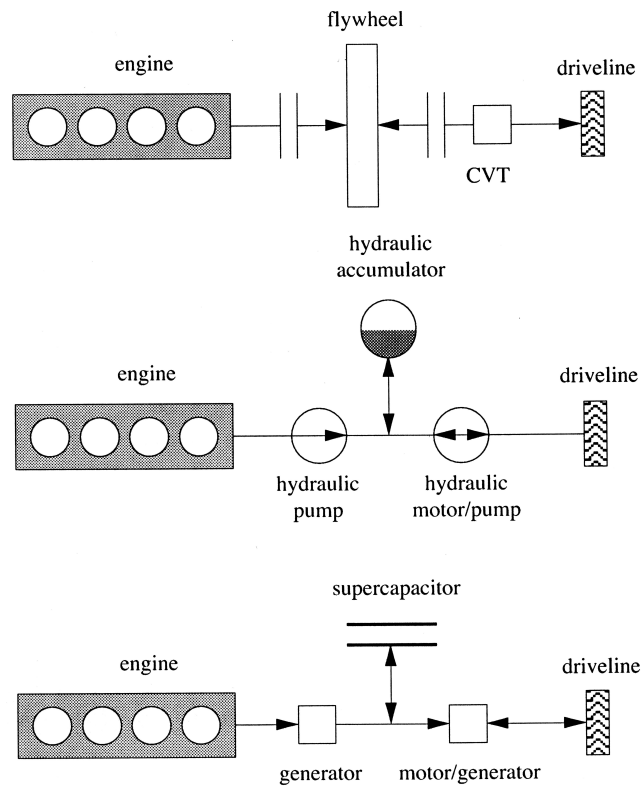


TSFS03 Vehicle Propulsion Systems

Project Compendium

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Preface

During the course we sometimes see that it is beneficial for you if we add more information and support material. This information will be made available on the course home page.

Notes about examination requirements

To get a pass (grade 3) on the course it is necessary to submit written reports with correct solutions for:

- all mandatory tasks in the project assignments 1, 2, and 3

To get a higher grade than 3 it is necessary to complete additional tasks (called extra tasks). The grade is determined by a point system where each additional task gives a maximum of 2-14 points. The sum of the points is then used to determine the grade, and requirements for higher grades are:

Grade 4: 14 points or more

Grade 5: 24 points or more

It is only possible to hand in the extra tasks once and they are graded in steps of 0.5 points. The tasks will be corrected when you hand them in, but there is a last day to hand in the extra tasks given on the home page.

Format requirements on the report

The reports should be submitted on the course page in Lisam. Login at lisam.liu.se, enter the course page "Vehicle Propulsion Systems" and press submissions in the menu to the left. On the submissions page, all the mandatory tasks have one submission folder each. Enter the folder specified for the task you want to submit and upload your report. In Lisam, the time window for each submission folder is displayed, make sure you submit your report before the submission deadline (which is also displayed on course web page). **It is mandatory for the report you submit to fulfill the following requirements**

- full written reports must be handed in to each assignment. Note that key equations used are to be given in the report, as well as conclusions and plots including labels on the axes.
- reports in PDF-format.

- append the code that you have written to solve the problem, and include the important code segments in the report.
- use the following naming convention:
`firstname_lastname_project_X.pdf` where X is the hand-in number.
- structure of your reports needs to follow the templates provided on the course page.
- submit the report on the course page in Lisam. For late submissions, in case it is not possible to submit in Lisam, reports should be emailed to one of the assistants of the course.

Acknowledgments

This course and assignments would not have been accomplished without the help of many persons who deserve credit. The course and in particular the assignments have been spawned from a PhD course where the participants contributed with the basis for the assignments. During the years the assignments have been polished and reformulated based on feedback from assistants and students. I wish to mention all that have contributed with assignments, improvements, and solutions: Xavier Llamas, Anders Fröberg, Erik Hellström, Maria Ivarsson, Emil Larsson, Andreas Myklebust, Vaheed Nezhadali, Martin Sivertsson, and Per öberg. Finally, Christofer Sundström is especially credited for both designing one of the assignments and for constructive refinements of the compendium. Thanks to all of You that have contributed!

Linköping, November 2013
Lars Eriksson

Projects 1

Basics of Energy Consumption Analysis

Purpose

This project assignment uses the demand driven analysis and applies it to cover the basic concepts of energy consumption of vehicles: longitudinal motion of a vehicle, minimum energy demand for a vehicle in a driving cycle, hand calculations for estimating fuel consumption, and gives a first step into computer tools for estimating the power requirements and energy consumption. Despite their simplicity and ease of implementation, these concepts are very useful in practical situations.

Examination requirement

- All tasks specified as “Task” in Sections 1.2 1.2.3 must be completed.
- Tasks specified “Extra Task” are for grades higher than 3.
- Format requirement on the report:
A written report must be handed-in (in PDF-format), the Matlab-code for the assignment should also be provided. Note that the key model equations used in the assignment are to be included in the report.

1.1 Introduction

This assignment deals with drive cycles and energy consumption of conventional powertrains. The energy consumption on common drive cycles are estimated by calculations by hand as well as simulations in the QSS toolbox.

Prerequisites for the task:

- familiarity with the first three chapters in the Vehicle Propulsion Systems book, [1].
- an installation of Matlab/Simulink on a computer.

- downloaded and installed QSS from the course homepage. To be able to run QSS its directory and sub-directories need to be added in MATLAB FILE -> SET PATH. Alternatively, use the command

```
addpath(genpath('fileDirectory'))
```

1.2 Assignments

Constants that are useful for the assignment are provided in Table 1.1. The drive cycles are found as MATLAB data files in `Data/DrivingCycles` in the QSS toolbox directory structure. If there are several similar cycles provided, use the one for a car with manual transmission, e.g. `NEDC_MAN`.

The example car used is a mid-sized sports car with a naturally aspirated gasoline V6 engine and a 5-speed manual transmission. Parameters of the vehicle are given in Table 1.2 and Table 1.3, and a payload of 100 kg has been added to the total mass.

Explanation	Parameter	Value	Unit
Acceleration due to gravity	g	9.81	m/s ²
Air density	ρ_a	1.18	kg/m ³
Gasoline lower heating value	q_{LHV}	44.6	MJ/kg
Gasoline density	ρ_f	737.2	kg/m ³

Table 1.1: Constants

Parameter	Value	Unit
Body		
Total mass	1400	kg
Fraction of total mass rotating	8	%
Frontal area	1.9	m ²
Air drag coeff.	0.3	-
Roll. res. coeff.	0.01	-
Wheel radius	0.3	m
Engine geometry		
Cylinders	6	-
Stroke	79.5	mm
Bore	82.4	mm
Inertia	0.2	kg m ²
Performance during traction		
Indicated engine efficiency	0.35	-
Loss mean effective pressure	1.5	bar
Performance during idling		
Indicated engine efficiency	0.3	-
Loss mean effective pressure	1.8	bar
Engine speed	750	rpm

Table 1.2: Car data.

Parameter	Value	Unit
Mechanical efficiency	0.98	-
Constant term in losses	0.3	kW
Ratio gear 1	13.0529	-
Ratio gear 2	8.1595	-
Ratio gear 3	5.6651	-
Ratio gear 4	4.2555	-
Ratio gear 5	3.2623	-

Table 1.3: Transmission data

Parameter	Interval	Unit
Mass m_v	[2100,1000]	kg
Frontal area A_f	[1,2]	m ²
Air drag coeff. c_d	[0.1,0.4]	-
Roll. res. coeff. c_r	[0.005,0.02]	-

Table 1.4: Parameter intervals.

1.2.1 Drive Cycles

In this section, there are two exercises that study drive cycles. The energy required to fulfill the drive cycle is quantified by the mean tractive effort. These values are then converted into equivalent quantities of gasoline.

The mean tractive force is defined in [1] as

$$\bar{F}_{trac} = \frac{1}{x_{tot}} \int_{t \in trac} F(t) \cdot v(t) dt \quad (1.1)$$

and the contributions are assumed to stem from aerodynamic, rolling resistance and acceleration resistance forces,

$$\begin{aligned} \bar{F}_{trac,a} &= \alpha \cdot \frac{1}{2} \rho_a A_f c_d \\ \bar{F}_{trac,r} &= \beta \cdot m_v g c_r \\ \bar{F}_{trac,m} &= \gamma \cdot m_v. \end{aligned} \quad (1.2)$$

The coefficients α, β, γ can be identified from the equations in the slides, and they mainly depends on the drive cycle. However, since the time in traction mode, $t \in trac$, depends on the vehicle there is also a minor vehicle dependency.

Task 1: Mean Tractive Effort

Make a MATLAB function that takes the cycle and vehicle parameters and calculates the coefficients α, β, γ from a drive cycle. How do these coefficients vary with the model parameters used in the calculation? Consider the NEDC, FTP-75, and WLTP cycles and the case of no recuperation for the interval of parameters in Table 1.4. Also, compute the fraction of the cycle duration that is spent in traction mode [%], the mean speed [m/s], the idling time [s] and total cycle length [km]. For this exercise, it is sufficient to study the following two extremes.

$$\begin{aligned} \text{config. 1: } \{m_v, A_f, c_d, c_r\} &= \{1000, 2, 0.4, 0.02\} \\ \text{config. 2: } \{m_v, A_f, c_d, c_r\} &= \{2100, 1, 0.1, 0.005\} \end{aligned}$$

Present the results in a table with the structure as in Table 1.5. Further, explain why vehicle configuration 1 and vehicle configuration 2 leads to the extreme values of α , β , and γ .

	NEDC		FTP-75		WLTP	
	Cnf 1	Cnf 2	Cnf 1	Cnf 2	Cnf 1	Cnf 2
Mean speed [m/s]						
Idling time [s]						
Total cycle length [m]						
Fraction in traction						
$[\alpha, \beta, \gamma]$						

Table 1.5: The structure of the table used for presentation of the results in task 1.

Task 2: Energy Consumption

Compute the required energy *at the wheel* in liter gasoline per 100 km for the example car in the NEDC FTP-75 and WLTP cycles without recuperation. Show the contributions from aerodynamic, rolling resistance and acceleration resistance respectively. Use the car parameters in Table 1.2 and use your function to calculate the drive cycle coefficients α , β , and γ from the two extremes in task 1.

Explain the differences between the driving cycles and how this correlates to the computed parameter values of α , β , and γ .

1.2.2 Fuel Consumption Estimate

The fuel consumption of the example car is now to be estimated. This is first done by calculations by hand and then through computer simulations.

In these calculations, assume that the power consumed by auxiliary units is 8% of the average produced engine power during traction.

Task 3: Average Operating Point

By the average operation point method, derive an estimate of the fuel consumption in the NEDC cycle. Use the average of the cycle parameters previously calculated. Further, assume a mean piston speed of 5.9 m/s, that corresponding to about 2200 rpm for the current car. The efficiencies of the powertrain components, power losses due to auxiliary units and idling losses should be considered.

Note that the engine geometry is to be used when computing the mean piston speed at idle.

Task 4: Quasi-static Simulation

Implement a model of the considered car in QSS. Open the Library and create a new Simulink model for your car, then take components from the QSS library and drag them into your model. Simulate the average fuel consumption for the NEDC manual and the FTP-75 cycles. How do the values change when cold-start

losses are taken into account (this is selected in the block *Tank*)? Compare, for NEDC manual, with the estimate calculated by hand. Include a figure of the top level of the finished model and tables where all parameters for the respective subsystem are stated. Present the results in a table with a structure as in Table 1.6.

	With cold start	Without cold start	From Task 3
NEDC manual			
FTP-75			-

Table 1.6: The structure of the table used for presentation of the average fuel consumption in task 4.

For the combustion engine modeling in QSS, use the Willans approximation. The maximum boost ratio parameter should be set to one since the considered engine is naturally aspirated. Assume further that the gas exchange losses is, in average, 0.5 bar. Regarding fuel cut-off, use a threshold of 5 Nm and zero power output (please note the sign convention in QSS and enter a number with the right sign). Other model parameters can be either identified or calculated from the parameters that have been given.

1.2.3 Electric Vehicle Centered Tasks

The interest for electromobility is growing and there are a lot of discussions around vehicles, batteries, and range. Therefore we are going to use the analysis tools for energy consumption over cycles developed above to gain some more insights. Two topics related to customer issues will be covered. Document your calculations in relation to the cycle analysis tools. In this task the intention is that you should use data for an electric car and the suggestion is that you in this case use the Tesla Model 3 Long Range Dual motor vehicle, unless stated otherwise, the vehicle is well documented with a lot of information and data available on the internet. Some vehicle data for electric vehicles are provided in Table 1.7.

	Nissan Leaf 2016	Nissan Leaf 2019	Tesla Model 3
Total mass [kg]	1505	1580	1919
Frontal area [m^2]	2.28	2.28	2.34
Air drag coefficient	0.29	0.292	0.24
Rolling coefficient	0.01	0.01	0.01
Battery size [kWh]	24	40	74
Useable battery [kWh]	22	36	70
Range NEDC [km]	199	350	n/a
Range WLTP [km]	n/a	250	442

Table 1.7: Parameters for some electric vehicles. Nissan 2016 does not have fuel consumption numbers for WLTP since it is too old while Tesla doesn't have NEDC consumption, since it is too new.

Task 5: Certification cycles and electric range

The first issue is the certification of the range, which is done using driving cycles, and when we change the driving pattern we will get another range. For example, if the customer has a car that has 500 km as certified range in NEDC, and want to go on a long drive between two cities at highway conditions, then the range will not be 500 km, and customer will be disappointed. Media has pointed out that we don't get the fuel consumption or electric range that the companies are advertising. The problem is not what the companies are reporting because the testing follows given standards, meant to give us as customers the ability to compare two vehicles against each other, the problem is that the cycles don't represent our driving.

1. Suppose that we have designed an electric vehicle for a range of 500 km in NEDC. What will the range be if we run it in the WLTP assuming that the powertrains have the same efficiency for the different cycles?
2. Consider a drive cycle of 100 km with the 3 components
 - (a) First 30 seconds of constant acceleration from 0 to v
 - (b) Constant velocity v
 - (c) Last 50 seconds of constant deceleration from v to 0.

Use this drive cycle to calculate the α, β, γ coefficients for $v=50, 70, 90, 110,$ and 120 km/h and compare these to the drive cycles you calculated in Task 1.

3. Suppose now that we have designed an electric vehicle for a range of 500 km in NEDC. What would the range be if we were driving on the highway at 120 km/h?

Task 6: Development of batteries and vehicles

Now we are going to look at EV powertrain efficiency (including the consumption of auxiliary devices) in conventional vehicles we are talking about tank-to-miles, here we will talk about battery-to-miles. Battery and vehicle data for the Nissan leaf 2016 and 2019 models (i.e. batteries with 24 kWh and 40 kWh respectively), as well as Tesla Model S 70D are given in Table 1.7. Look at the rated NEDC range, and their battery's energy and give an estimate of the average efficiency of the electric powertrain for the three vehicles. Perform the same comparison for published WLTP data. Are all efficiencies below one? Explain your results.

Task 7: Overrating costs fuel economy

The final question on electric vehicles is over-dimensioning of the vehicle to cover the most extreme range scenario gives a penalty on the energy consumption of the vehicle. Consider a Nissan leaf designed for 199 km in NEDC. Suppose that I would like to have a vehicle with 500 km in NEDC. (Consider battery density = 130 Wh/kg)

1. What battery size would I need to have to get that range and necessary energy and how much extra mass will the car have?

- In the end, how much more energy would the vehicle with a long range require in the NEDC, meaning how much more electricity would you need in normal/city driving?

1.3 Extra tasks

The following tasks are for grades higher than 3.

Extra task 1: Tolerances on velocity profile

2 p

The velocity profiles that are specified have tolerances, stating that you are allowed to deviate from the nominal profile with ± 1 km/h. These tolerances have an effect on the fuel consumption, but how large can they be?

Compute the required energy *at the wheel* in liter gasoline per 100 km for the example car in the FTP-75, NEDC, and WLTP cycles without recuperation, for the three cases: nominal profile, maximum velocity profile, and minimum velocity profile. State your assumptions and explain the results.

Extra task 2: Mild hybrid with stop-go functionality

2 p

Investigation of mild hybrid, with only stop-go functionality. How much fuel is saved if the engine is shut off during the idle periods in the cycle? Use the conventional vehicle in QSS described above to study this effect.

1.3.1 Extra task using forward modeling

In this task forward simulation is used, i.e. the model is based on dynamic equations. In order to perform the task, a simulation model can be downloaded from the course home page. There are three driving cycles available and you need to load one of these before you start the simulation. These driving cycles include more information than the driving cycles available in QSS.

Extra task 3: Compare quasi stationary and dynamic modeling

4 p

The objective of this task is to get an understanding of the differences between quasi stationary simulation and forward simulation. You are supposed to parametrize the given model to represent the sports car. Assume that all components except the chassis have zero mass. Note that for some components you need to parametrize the controller as well.

Compare the simulated fuel consumption and simulation time using QSS and the dynamic model. Explain the differences, especially in simulation time. Present the values of the parameters used. It is only necessary to present the values of the parameters that differ from the values from Task 4 that was done in QSS, if any.

The component models used in the dynamic model are very similar to the models in QSS. In cases where there are differences in the parametrization of the models, try to set values making the models as comparable as possible.

1.3.2 Transmission

It is a known fact in the business that if you have the same car with a manual and an automatic transmission that have similar gear ration. Then the vehicle with automatic transmission will have higher fuel consumption, since the automatic gearbox has lower efficiency, there is a torque converter with losses and there are this is due

A 4-speed automatic transmission is designed for the car studied here that gives about the same fuel consumption. The gear ratios are given in Table 1.8. Assume the same amount of average idling losses as for the manual transmission, see Table 1.3. Use the model in QSS from previously.

Gear	Ratio
1st	2.89
2nd	1.57
3rd	1.00
4th	0.69
Final drive	3.77

Table 1.8: Automatic transmission data.

Extra task 4: Manual vs Automatic Transmissions

5 p

Simulate the fuel consumption on NEDC manual presuming that there is no difference in the average efficiency between the automatic and manual transmission. Explain the difference in the consumption in terms of change in engine operating points.

It is known that the fuel consumption is about the same in reality for the studied car. What average efficiency of the automatic transmission is thereby implied? Hence, use simulations to find out the lowest required average efficiency of the automatic transmission yielding the same fuel consumption as with the manual transmission.

Use the block *Manual Gear Box* in QSS to make a simple model of the automatic transmission and use the same ratio for the 4th and 5th gear.

Projects 2

Dynamic Programming Optimization of Hybrid Vehicle Fuel Consumption

Purpose

Acquire knowledge and experience concerning how to solve optimal control problems using Deterministic Dynamic Programming DDP. Acquire knowledge about the differences between parallel and series hybrid configurations and their properties.

Examination requirement

- All tasks specified in Section [2.2.2](#) must be completed.
- Tasks specified in Section [2.3](#) are for grades higher than 3.

2.1 Introduction

For environmental reasons as well as economical, minimization of fuel consumption is an urgent problem to solve. The hybrid vehicle with its possibility of charging and discharging battery gives us a mean to reduce fuel consumption. The challenge is to design a control that decides when to use the electrical motor and when to run the engine. If the driving mission is not known, this is a difficult task. Depending on the driving cycle (speed, gearshifts, topography) the fuel consumption is reduced more or less when using a common hybrid vehicle. If the driving cycle is not known it is also important to have safety margins so that the battery isn't completely discharged.

However, if the driving cycle is known it is possible to find the global minimum of fuel consumption, i.e. the best way possible to control the vehicle. One way of finding the global minimum is by using dynamic programming. The dynamic programming for this assignment finds the minimum by dividing the driving cycle in sections and gets the optimal control from each interior position to the end of the driving cycle.

Prerequisites for the task

- Chapters 1-4 and Appendix III in the Vehicle Propulsion Systems book, [1]. Only parts of chapter 4 is needed to solve the task.
- Case study 2 in the Vehicle Propulsion Systems book, [1].

2.2 Assignments

A hybrid vehicle has various possibilities of configurations. The parallel and the series hybrid vehicle are two well known concepts. The parallel hybrid has a mechanical link (via transmission) from the combustion engine to the wheels. In the series hybrid the combustion engine charges the battery and the electrical motor is connected to the output shaft. This means that for the parallel hybrid only the state of charge is optimized, while the series hybrid has the possibility of controlling both state of charge and the rotational speed of the engine.

The models for the parallel and the series hybrid, should be formulated so that the cost for following an arc in the optimal control problem can be calculated.

2.2.1 Information and data

Vehicle Parameters

Parameters for vehicle, driveline, engine, battery and electrical motor are given in the following three tables: Table 2.1 gives the parameters that are common for both configurations, Table 1.3 gives the parameters for the transmission (neglect the constant losses in the gearbox) that are to be used in the parallel hybrid, and Table 2.2 gives the parameters specific for the series hybrid. In the series hybrid, it is not possible to get $N_e > 800\text{rpm}$ in the time step when the engine is started. In this time step the engine is not capable of delivering any torque to the driveline.

Driving cycles

Many different driving cycles are used for simulation and certification purposes. The two driving cycles to be used here specifies speed [m/s], gear [-], acceleration [m/s^2] and time [s]. The extra-urban driving cycle (`EUDC_MAN_DDP.mat`) starts by ramping up speed, which is continued by cruising on highway, and finally speed is ramped down. The city driving cycle (`City_MAN_DDP.mat`) represents accelerations and stops that could occur in a city environment. The driving cycles are available on the homepage, and are only slightly modified in the gear selection at almost stand still compared to the driving cycles included in QSS.

Cost function

The cost function is the function that is minimized by the dynamic programming. The objective of this assignment is to minimize the fuel consumption. This must be reflected in the cost function.

Also the states in the final time step could hold a cost. If there is no cost related to the final time step, the final state will be the one that requires the least fuel along the driving cycle, e.g. resulting in a low state of charge.

Vehicle parameter	Denomination	Value	Unit
Lower heating value	H_l	44.6e6	J/kg
Fuel density	ρ_l	737.2	kg/m ³
Air density	ρ_a	1.18	kg/m ³
Engine inertia	J_e	0.2	kgm ²
Engine maximum torque	$T_{e,max}$	115	Nm
Engine displacement	V_d	$1.497 \cdot 10^{-3}$	m ³
Number of revolutions per stroke	n_r	2	-
Engine weight	m_e	1.2	kg/kW
Willans approximation of engine efficiency: (definition of parameters according to p.46 in VPS)			
	e	0.4	-
	$p_{me,0}$	0.1	MPa
Battery charging capacity	Q_0	6.5	Ah
Open circuit voltage	U_{oc}	300	V
Maximum dis-/charging current	I_{max}	∓ 200	A
Inner resistance	R_i	0.65	Ω
Battery weight	m_{batt}	45	kg
Efficiency of electrical motor and generator	η	0.9	-
Maximum torque of electrical motor and generator	$T_{em,max}$	400	Nm
Maximum power of electrical motor and generator	$P_{em,max}$	∓ 50	kW
Electric motor weight	m_{em}	1.5	kg/kW
Maximum powertrain power	$P_{pt,max}$	90.8	kW
Drag coefficient	C_D	0.32	-
Rolling resistance coefficient	C_r	0.015	-
Frontal area	A_f	2.31	m ²
vehicle mass	m	1500	kg
wheel radius	r_w	0.3	m
inertia of the wheels	J_w	0.6	kgm ²

Table 2.1: Common vehicle parameters for the two hybrid vehicle configurations

Vehicle parameter	Denomination	Value	Unit
Allowed engine speed range	N_e	[0, 800...5000]	rpm
Maximum acceleration in the engine	$\dot{\omega}_e$	300	rad/s ²

Table 2.2: Additional powertrain parameters

2.2.2 Tasks

Task 1: Modeling and optimization of the parallel hybrid

Go through the following tasks for the parallel hybrid vehicle. The result of task 1.1b may be omitted from the report, however, make sure your arc-costs match the values provided below.

- 1.1 a) Model the hybrid concept. Collect and compile the model equations and collect parameter values for the components in the vehicle.
- 1.1 b) Evaluate the arc-costs for the following cases in the parallel hybrid where the syntax is

```
parallelhybrid([t_start t_end], SoC_start, SoC_end)
```

- A constant speed point : [15 16]
- A stand still point : [4 5]
- An acceleration point : [59 60]
- A deceleration point : [158 159]

- parallelhybrid([15 16], 0.5, [0.49 0.498 0.50 0.501 0.51])
parallelhybrid([4 5], 0.5, [0.49 0.498 0.50 0.501 0.51])
parallelhybrid([59 60], 0.5, [0.49 0.498 0.50 0.501 0.51])
parallelhybrid([158 159], 0.5, [0.49 0.498 0.50 0.501 0.51])

and City drive cycle is used.

The arc costs given the data above are:

$[\text{inf } 0 \ 1.75 \ 6.35 \ \text{inf}] \cdot 10^{-4} \text{ kg.}$
 $[\text{inf } \text{inf } 0 \ \text{inf } \text{inf}] \cdot 10^{-4} \text{ kg.}$ or $[\text{inf } 0 \ 0 \ \text{inf } \text{inf}] \cdot 10^{-4} \text{ kg.}$
 $[\text{inf } 4.43 \ 10.79 \ 15.39 \ \text{inf}] \cdot 10^{-4} \text{ kg.}$
 $[\text{inf } 0 \ 0 \ 2.54 \ \text{inf}] \cdot 10^{-4} \text{ kg.}$

Please note that the values may vary depending on the implementation. Though, this variation is not very large. Given the test scenarios, motivate whether or not your arc calculations are correct writing a short explanation. Why the value is infinite or zero in certain SOC combinations?

- 1.1 c) How much do the electric components in the hybrid vehicle weight?
- 1.1 d) For a conventional vehicle to have the same maximum power as the hybrid powertrain, how much larger would the combustion engine have to be? How much extra weight would this add to the powertrain?

Hint: The maximum powertrain power has to be computed taking into account the power curves of the electric motor and the combustion engine as well as the component losses. This calculation is already done and the value is provided in Table 2.1, ($P_{pt,max}$).

Next we are going to use deterministic dynamic programming (DDP) to find the optimal control trajectories of the hybrid vehicle for a couple different cases. For all cases calculate the fuel consumption for the optimal solution in [l/100km], also measure the computational time of the DDP algorithm. Evaluate all tasks on both City and EUDC cycles, and put your results in a table.

- 1.2 a) How do you make sure that the strategy is charge sustaining?
Hint: Check how DDP works and how one can make sure that an undesired final step is not selected. This will require you to add a suitable final cost to some of the states.
- 1.2 b) Run the optimization for a conventional vehicle with the same maximum power as the hybrid powertrain.
Hint: Use the masses and scaling factors computed in 1.1 e-f. A convenient way of “removing” the battery is to construct a state vector so that all combinations violate a component limitation. This prevents the algorithm from changing the current value of the battery SOC.
- 1.2 c) Rerun the same optimization as in 1.2 b) but now use the downsized engine from the hybrid powertrain.
- 1.2 d) Run the optimization for the hybrid powertrain but restrict the algorithm as done in 1.2 b) so it cannot use the battery.
- 1.2 e) Now run the DDP-algorithm for the full hybrid, allowing battery use. Plot the results including optimal SOC and cost profiles. Tabulate your final optimal costs.

Task 2: Modeling and optimization of the series hybrid

Go through the following tasks for the series hybrid vehicle. The result of task 2.1b may be omitted from the report, however, make sure your arc-costs match the values provided below.

- 2.1 a) Model the hybrid concept. Collect and compile the model equations and collect parameter values for the components in the vehicle.
Note: The electric machine limits should only be implemented on the generator.
- 2.1 b) Evaluate the arc-costs for the following cases in the series hybrid where the syntax is

```
serieshybrid([t_start t_end], SoC_start, SoC_end, N_start, N_end)
```

- A constant speed point : [15 16]
- A stand still point : [4 5]
- An acceleration point : [59 60]
- A deceleration point : [158 159]
- serieshybrid([15 16], 0.5, [49 49.8 50 50.2 51]e-2, 3e3, 3e3)
serieshybrid([4 5], 0.5, [49 49.8 50 50.2 51]e-2, 3e3, 3e3)
serieshybrid([59 60], 0.5, [49 49.8 50 50.2 51]e-2, 3e3, 3e3)
serieshybrid([158 159], 0.5, [49 49.8 50 50.2 51]e-2, 3e3, 3e3)
- serieshybrid([15 16], 0.5, [0.5], 3e3, [0 2 3 5]e3)
serieshybrid([4 5], 0.5, [0.5], 3e3, [0 2 3 5]e3)
serieshybrid([59 60], 0.5, [0.5], 3e3, [0 2 3 5]e3)
serieshybrid([158 159], 0.5, [0.5], 3e3, [0 2 3 5]e3)

- `serieshybrid([15 16], 0.5, [0.499 0.5], 0, [0 8 20]e2)`
`serieshybrid([4 5], 0.5, [0.499 0.5], 0, [0 8 20]e2)`
`serieshybrid([59 60], 0.5, [0.499 0.5], 0, [0 8 20]e2)`
`serieshybrid([158 159], 0.5, [0.499 0.5], 0, [0 8 20]e2)`

and City drive cycle is used.

The fuel consumption from the twelve function calls above should be in the range of :

$$\begin{aligned}
 & \begin{bmatrix} \text{inf} & 0.21 & 0.28 & 1.24 & \text{inf} \end{bmatrix}^T \cdot 10^{-3} \text{ kg}, \\
 & \begin{bmatrix} \text{inf} & 0.21 & 0.21 & 1.17 & \text{inf} \end{bmatrix}^T \cdot 10^{-3} \text{ kg}, \\
 & \begin{bmatrix} \text{inf} & 0.28 & 1.07 & 2.03 & \text{inf} \end{bmatrix}^T \cdot 10^{-3} \text{ kg}, \\
 & \begin{bmatrix} \text{inf} & 0.21 & 0.21 & 0.83 & \text{inf} \end{bmatrix}^T \cdot 10^{-3} \text{ kg}, \\
 & \begin{bmatrix} \text{inf} & 0 & 0.28 & 1.33 \end{bmatrix} \cdot 10^{-3} \text{ kg} \\
 & \begin{bmatrix} \text{inf} & 0 & 0.21 & 1.26 \end{bmatrix} \cdot 10^{-3} \text{ kg} \\
 & \begin{bmatrix} \text{inf} & 0.73 & 1.07 & 2.12 \end{bmatrix} \cdot 10^{-3} \text{ kg} \\
 & \begin{bmatrix} \text{inf} & 0 & 0.21 & 1.26 \end{bmatrix} \cdot 10^{-3} \text{ kg} \\
 & \begin{bmatrix} 0 & 6.7 & \text{inf} \\ \text{inf} & \text{inf} & \text{inf} \end{bmatrix} \cdot 10^{-5} \text{ kg} \\
 & \begin{bmatrix} 0 & 6.7 & \text{inf} \\ 0 & 6.7 & \text{inf} \end{bmatrix} \cdot 10^{-5} \text{ kg} \\
 & \begin{bmatrix} \text{inf} & \text{inf} & \text{inf} \\ \text{inf} & \text{inf} & \text{inf} \end{bmatrix} \cdot 10^{-5} \text{ kg} \\
 & \begin{bmatrix} 0 & 6.7 & \text{inf} \\ 0 & 6.7 & \text{inf} \end{bmatrix} \cdot 10^{-5} \text{ kg}
 \end{aligned}$$

Observe that the fuel consumption could vary depending on some choices in the implementation. The consumption should though be in the same range as given above. Explain why some costs are infinite and zero. This means, state which limitation that causes this in each case.

Next we are going to use DDP to find the optimal control trajectories of the hybrid vehicle for a couple different cases. For all cases calculate the fuel consumption for the optimal solution in [l/100km], also measure the computational time of the DDP algorithm. Evaluate all tasks on both City and EUDC cycles.

- 2.2 a) Make sure that the strategy is charge sustaining by adding a suitable cost to some states in the final step.
- 2.2 b) Run the algorithm but restrict it so the battery remains unused.
- 2.2 c) Run the algorithm for the full hybrid. Plot the results including optimal SOC, engine speed and cost profiles. Tabulate your final optimal costs.

Task 3: Evaluation of results

- Which hybrid vehicle configuration requires the longest computational time to find optimal control by using dynamic programming? How big is the difference? Is this consistent with the complexity of DDP algorithm? The time complexity can be described by the notation $\mathcal{O}(t^x m^y n^z)$ where t , m , and n are the size of the time and state grids respectively.

Derive and state the theoretical exponents x , y , and z for the parallel and series hybrids.

- How large consumption decrease comes from the downsizing of the engine and how much comes from the hybridization? Are there any drawbacks of just downsizing?
- Which hybrid configuration gets the lowest fuel consumption for the EUDC and City driving cycle respectively? Explain why. What can be said about the powertrain efficiencies?

2.3 Extra tasks

If you are interested in optimal control of hybrid vehicles, the following issues may be analyzed further

Extra task 1: More driving cycles 2 p

Analyze 4 additional driving cycles (eg. FTP-75, MVEG-95, Japan, WLTP ...) in terms of fuel consumption and find optimal control for these. In each case where there is a configuration that is better, explain why that configuration is best.

Extra task 2: Optimize the vehicle configuration 4 p

Optimize (or tune) the vehicle parameters (combination of engine and battery sizes etc) to give a better fuel consumption than the ones suggested above. Try to find an optimum and provide an explanation for why these new parameters were chosen.

Extra task 3: Gear ratios in the parallel hybrid 2 p

The gear ratios used in the mandatory task represent the sports car that also is used in Hand in 1. Investigate how a modified gearbox with gear ratios according to Table 2.3 will affect the fuel consumption. Explain the results and calculate how many revolutions per minute the engine will run using the different gearboxes. Are there any drawbacks using the gearbox with lower gear ratios? Which gearbox do you think most drivers would prefer? Note that the gear ratios in this task includes the gear ratio in the final gear.

Gear	Gear ratio
1	9.97
2	5.86
3	3.84
4	2.68
5	2.14

Table 2.3: Gear ratios in the modified gearbox.

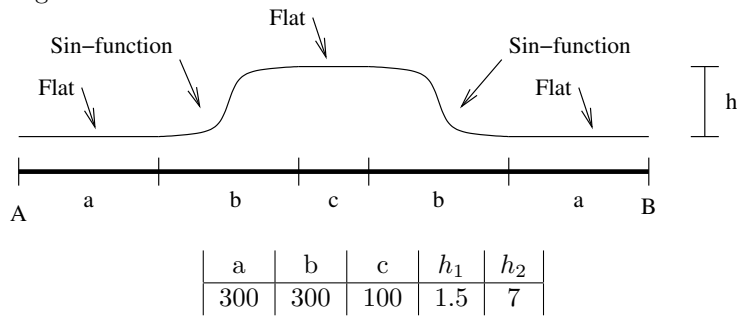
Extra task 4: Heavy truck problem

12 p

Now we will study the possibilities that arise if the vehicle is a heavy truck and the driving cycle contains information about topography. For heavy trucks seemingly small slopes pose challenges for maintaining the vehicle speed. This is a problem that actually can be turned to an advantage for saving fuel. By knowing the topography and considering the kinetic and potential energies as energy storage.

For heavy trucks in long haul operation a typical scenario would be to go from A to B in a specified time, i.e. essentially the average speed is specified. Then the truck is allowed to deviate from this average speed and the goal is to minimize the fuel consumption. To solve this problem it is necessary to use two states, one for the vehicle speed and one for the traveled distance.

Find the optimal control trajectories for a heavy truck in the following two hilly topographies, where the trajectories have all parameters the same except for the height h .



These different profiles will result in solutions that have different characteristics. Give a motivation for the characteristics of the solutions.

The average speed from A to B should be 80 km/h. A heavy truck often has a payload of up to 60 000 kg and an engine with a maximum power of 650 hp.

$m=$	60 000 kg	$C_r=$	0.007	$C_D=$	0.8
$A_f=$	10 m ²	$r_w=$	0.52 m	$e=$	0.49
$T_{e,max}=$	2000 Nm	$V_D=$	12e-3 m ³	$p_{me,0}=$	9e4 Pa
$i_g=$	3.27	$N_{max}=$	2500 rpm	$N_{min}=$	600 rpm

Table 2.4: Data for the heavy truck model used in the hilly topography. Engine and wheel inertias etc are assumed to be negligible in comparison to the vehicle weight in the heavy truck case.

Hints:

- To get a good resolution in the solution of the traveled distance state without having a large state space that increases the computational time, it is beneficial to parameterize the traveled distance in terms of a deviation from the traveled distance at the average speed.
- The states *traveled distance* and *vehicle speed* are coupled and therefore the grid spacing must also be coupled.

- One special thing with this problem is that there is only one degree of freedom when looking at the controlled variable but there is a 2D space, and therefore the search procedure for each time step can be optimized so that it is only performed in one dimension.

Extra task 5: Slope for changed solution

2 p

Use your insight about the system properties to give an analytical solution for the height h for when the solution to the optimal control changes character. Verify this in simulation by utilizing the code from the previous extra task.

2.4 Support Code & Hints

In this task you have the possibility to either write the solver for the dynamic problem yourself or use the provided functions.

Matlab scripts for dynamic programming

The following Matlab scripts have been made available for you to perform the optimization by dynamic programming:

- `testHybrids.m` - Template for the script for running the tests.
- `dynProg1D.m` - Solver for dynamic programming problems with 1 state.
- `dynProg2D.m` - Solver for dynamic programming problems with 2 states.
- `parallelHybrid.m` - Function template for calculating the arc costs.
- `seriesHybrid.m` - Function template for calculating the arc costs.
- `Contents.m` - Help file with this information.

In the Matlab function `testHybrids.m` you will set up the problem that you will solve. The model equations and cost functions should then be implemented in the Matlab functions `parallelHybrid.m` and `seriesHybrid.m`.

2.4.1 Hints

- To save computational time it is a good idea to use the matrix formulation, as is indicated in the Vehicle Propulsion Systems book [1].
- To save time, use a truncated or shorter profile time when implementing and debugging your code for the concepts.

Projects 3

Real-time Optimal Control of Hybrid Electric Powertrains

Purpose

Acquire knowledge and experience about solving and implementing a real time energy management control strategy for a hybrid electric vehicle.

Examination requirement

- All tasks specified in Section 3.2.2 must be completed.
- Tasks specified in Section 3.2.3 are for grades higher than 3.

3.1 Introduction

In the previous task the optimal control solution to the energy management problem for hybrid electric vehicles was studied using dynamic programming. Dynamic programming is a powerful tool to study optimal control as well as to investigate the potential of different configurations. However, its computational burden, as well as requirement for perfect look-ahead make it difficult to implement in real-time energy management.

A common strategy in academia to solve the energy management problem in real time is equivalent consumption minimization strategy (ECMS). Instead of minimizing $\int_0^T \dot{m}_f dt$ which requires the entire driving mission to be known the problem is transformed to instead minimize a sum of power from fuel and battery at each timestep. However these powers are not directly comparable so an equivalence factor is needed. The resulting expression to be minimized is of hamiltonian form and can be written:

$$\begin{aligned} H &= P_f + \lambda P_{ech} \\ u^* &= \arg \min H \end{aligned} \tag{3.1}$$

where P_f is the power from fuel, P_{ech} the power in the battery, λ an equivalence factor and u^* the optimal control. This problem can be solved at each timestep, iff λ is known.

ECMS and Pontryagins maximum principle(PMP) are closely related. From the PMPs necessary conditions for optimality we have:

$$\frac{\partial H}{\partial x} = -\dot{\lambda}^* \quad (3.2)$$

where x are the states. This means that along the optimal trajectory, the optimal time evolution of the equivalence factor λ has to be equal to the partial derivative of the hamiltonian with respect to the state.

Prerequisites for the task

- Chapter 7 and Case Study 7 in the Vehicle Propulsion Systems book, [1].

3.2 Assignments

The assignment is to be solved by using the QSS program package that can be downloaded from the course homepage. A basic vehicle model called `HEV_ECMS.mdl` is provided on the course-page as well as two scripts `init_HEV_ECMS.m` and `parallelhybrid_ECMS.m` } that should be completed in the task. You should download this material before continuing with the assignment. Remember that you always can study the already implemented QSS examples and the QSS library if you are new so Simulink.

3.2.1 Information and data

Vehicle Configuration

The considered configuration is the parallel hybrid studied previously. The parameters of the provided model are not exactly the same so you will have to study the models to fill in the appropriate values.

3.2.2 Tasks

- Construct the Hamiltonian on paper, write down expressions for P_f and P_{ech} .
- Using your Hamiltonian and 3.2 what is the optimal time evolution of our equivalence factor, i.e. what is λ^* ? Justify your response analytically.
- Using the `parallelhybrid.m` from the dynamic programming exercise as base, complete `parallelhybrid_ECMS.m`, i.e. given $[\omega_{ice}, \dot{\omega}_{ice}, T_{req}, \lambda]$ your script should return the optimal $[T_{ice}, T_{em}]$
Hint: Solve the optimization numerically.
- Complete the models for the electric motor and combustion engine in `HEV_ECMS.mdl`, parametrize the gear box and vehicle model so it corresponds as close as possible to your `parallelhybrid.m` implementation. What is the function of `init_HEV_ECMS.m`? Also implement checks to see

that your controller does not violate any limits.

Hint: Study the battery and Torque following-subsystems. Remember to include the inertia of the wheels in the rotating mass field of the QSS Vehicle block (Note that the block requires a % value, look under the block mask to see how the model uses the rotating mass percentage and thus how you should compute its value). Include the engine inertia effects in the engine block and not in the vehicle rotating mass, as you did in your `parallelhybrid.m` implementation.

- Find the optimal solution to the EUDC manual and City manual cycles using ECMS. What is the optimal $\lambda(t)$ for the different driving cycles?
Note: *Due to discretization it can be hard to get $SOC(T) = SOC(1)$, but try to get as close as possible while ensuring $SOC(T) \geq SOC(1)$*
- Compare the received solutions to the solutions from dynamic programming. Are there any differences? Computational time?
- Use the driving cycles NEDC and FTP75. First find the optimal $\lambda(t)$. Secondly, do a sensitivity analysis on $\lambda(t)$, what happens if your open loop control is not perfect?
- Given that the problem is unconstrained, the problem in 3.1 can be solved analytically. Solve the problem and find an expression for the controls. You need to analytically ensure that your derived expression minimizes (and not maximizes) the Hamiltonian. When are the derived controls applicable? When not?

3.2.3 Extra Tasks

If you are interested in real time optimal control of hybrid vehicles, the following issues may be analyzed further

Extra task 1: Implementing analytical solution

3 p

Implement the analytical solution to the ECMS problem. Compare the optimal λ to the previous implemented version, are there any differences?

The following three extra tasks fit together in a sequence where the controller from the first can be used on the second and third and the results from the third and are to be compared to those of the second. The first extra task is not a prerequisite for the following three tasks.

Extra task 2: Adaptive ECMS

5 p

The ECMS strategy can be made adaptive by using the current and reference values of SOC, to implement an algorithm that adapts λ . Since this is control and we know the reference SOC and know that λ will influence SOC, we can implement a controller that controls SOC to its desired value.

Complement your vehicle model from above with a controller for SOC. Implement the SOC controller, preferably a PI-controller, that uses λ as control signal u and tune the PI parameters of the controller so it gives a smooth convergence of SOC to its desired value during NEDC and FTP-75. How much

difference in fuel consumption do you get with the optimal lambda and with this adaptive lambda.

3.2.4 Plug in hybrid vehicles

For a plugin hybrid electric vehicle we have a lot of electricity so we can drive all electric. Then there are some different control strategies discussed. Charge sustain which is the strategy for normal hybrids. Charge depletion is to run all electric to deplete the battery. Normally when the vehicle controller doesn't know how long we will drive it guesses that the driving is short so the preferred way if the driving range is shorter than the all electric range the cheapest option will be to run all electric, but if the driving does deplete the battery the controller needs to switch over to a charge sustain strategy. The allowed range for the SOC can be from 90% down to 10% to save lifetime of the battery.

Extra task 3: Charge Depletion - Charge Sustain

5 p

Modify the battery size in the vehicle so it gets an all electric range of about 200 km on the WLTP cycle. Implement a control strategy that performs Charge Depletion and then Charge Sustain (CDCS). Initially the vehicle has SOC 90% and then it is allowed to go to 15% but never go below 10% this can be achieved by using the adaptive ECMS you developed above for the new vehicle and use a set-point of 15% SOC. Evaluate your controller by constructing a cycle that repeats the WLTP 15 times (i.e. 347.1 km which is longer than the all electric range). How does your SOC vary? Can you show the CDCS behaviour? What is the fuel consumption over the 15 cycles?

Extra task 4: Charge Depletion - Charge Sustain

5 p

If you know that the distance that the vehicle will drive will be 15 WLTPs then you can consider a blended strategy that distributes the usage of electricity over the entire cycle, this is called a blended strategy. A simple blended strategy can be achieved by making a SOC reference trajectory so that $SOC(x)$, where x is the distance driven, will have a decay from 90% down to 15% when we reach 347.1 km. So it is blending in the usage of battery while driving when it is most useful.

Implement a blended strategy and compare it to the CDCS strategy from above. The strategy can be achieved by providing a distance dependent reference, for the SOC in the Adaptive ECMS, that decreases linearly with the distance driven. How do the strategies differ in terms of SOC over the driving distance? How much can be gained in fuel economy if we get information about the distance that will be driven to the next charging and don't have to guess that the driving is short?

Concluding remarks

The project with all its tasks reflect a development procedure that is a common feature in many engineering projects and in particular when designing complex mechatronic systems. The first step is to develop a robust low level system controller, then you build new functions upon that foundation and then on top of this second system, and so you continue to higher levels of abstraction. In

the end you have constructed a system that can be used to cope with and solve complex tasks.

In this particular example the ECMS and the minimization is performed with a given λ , this gives the foundation. You note that you can use λ to influence SOC. With this knowledge, you can, on top of this, build an SOC controller that adapts λ so you get your desired SOC. Then on top of this you can add the function to control SOC, first to get it down to your desired depletion level and then without changing the controller you automatically (automagically) get a charge sustain strategy at that level. In the end this becomes a CDCS strategy. Finally you can add functions on top of this, for example GPS based route planning, that just modify a set-point of the lower level controllers and in the end achieves a system that has a fairly complex functionality. This is an illustration of the principle of securing the foundation for each level and then successively adding features on top of that foundation in each step which is a core element in the development process in the system building industry.

Projects 4

Short Term Storage and Supervisory Control

This project is not mandatory, but is an extra task that gives up to 12 points.

Purpose

This assignment deals with short term storage systems. The task is to apply everything you have learned during the course to modify an existing vehicle by adding one or more short term storage systems. The goal is to minimize the fuel consumption for the new vehicle using a smart control strategy and by choosing gear ratios and sizes of the add-ons in an optimal way.

Examination requirement

- Three different concepts can be modeled, implemented, and analyzed.
- The demands on the contents of the final report stated in Section 4.1 must be fulfilled.
- Completing the supercap concept gives up to 8 points.
- Completing the flywheel concept gives up to 10 points.
- Completing the hydraulic concept gives up to 12 points.
- If you decide to do more than one concept 6 points will be deducted from the second and third concept.(This means doing only the flywheel concept gives 10 points, doing both supercap and flywheel concepts gives 12 points.)

4.1 Assignment specification

The assignment is to be solved by using the QSS program package that can be downloaded from the course homepage. A basic vehicle model called `OrdinaryVehicle.mdl`

is provided on the course-page as well as a script to make efficiency plots for energy converters (`mkPlots.m`). You should download this material before continuing with the assignment. Remember that you always can study the already implemented QSS examples and the QSS library.

Chapter 5 in the Vehicle Propulsion System book [1] covers short term storage systems, while Chapter 4 covers Hybrid-Electric propulsion systems.

The final report should at least contain the following

- The performance and engine efficiency plot of the conventional vehicle according to Section 4.1.1.
- Description and discussion of the final design and the design choices, as well as the model equations and model parameters.
- Description and discussion of the QSS implementation. You are free to use other available QSS model blocks than the ones used in the basic vehicle model as long as the models conforms to the specifications in Section 4.2.
- Description and discussion of your chosen control strategy.
- Efficiency plots showing in what operating points your components are operating. This is only necessary for components with a non constant efficiency and/or with torque/speed limits.

The report should be self explanatory and should not assume prior knowledge to any of the used short term storage systems or components. All assumptions should be discussed and the control strategy should be well described, discussed and motivated.

You should also make believable that your fuel consumption is accurate. That is, you should explain where your design saves the most fuel and how this affects the total fuel consumption.

Available model components and assumptions are listed in Section 4.2 below.

4.1.1 Evaluation of vehicle demands

The first assignment is to evaluate the provided vehicles performance and the drive cycles energy demand for the specific vehicle. Therefore answer the following questions:

- What is the maximum acceleration of the vehicle? This property can e.g. be given in the time to accelerate from 0 km/h to 100 km/h.
- What is the maximum speed of the vehicle?
- In what operating points does the engine operate when a driving cycle is used?

Approximate values for the first two questions are sufficient, and Chapter 2 in [1] is recommended. As a help for you to plot the operating points of the engine, there is a plot command `mkPlots.m` available for you to download.

4.1.2 Design of new vehicle

Choose a short term storage concept. You may for example choose one of the concepts from Figure 5.2 in [1]. However, you are free to connect any components you wish as long as it's physically feasible and provided that you add the components masses to the vehicle mass.

Write down the equations for all the components of the modeled vehicle. Then chose component sizes, gear ratios and other quantities. Plot finally the efficiency maps as well as limiting factors where applicable and ensure that

1. All operating points will be within the limits for the used components.
2. The components will be operating close to the maximum efficiency when working together.
3. The short term storage system[s] are large enough.

If you are uncertain of how to implement your concept in QSS you may look at the QSS built-in examples, especially *qss_example.shv*. Also remember that the Matlab/Simulink blocks *Scope* and *To Workspace* are your friends.

4.1.3 Design of control strategy

A control strategy is an algorithm that decides where to take the energy that is needed by the vehicle-drivecycle pair and how to utilize the short term storage. The control strategy should be designed so that the vehicle can perform the whole drive cycle without running into torque/speed limits and so that the combustion engine as well as the other components are operated in an efficient way.

4.1.4 Evaluation of new Vehicle and control strategy

Show how your vehicle/control-strategy works together. Use efficiency plots that show what operating points your components are operating in. Have you chosen the right gear ratios and sizes for your vehicle? Make a parameter study to see how sensitive your fuel consumption is to the model parameters for your short term storage components as well as your control strategy. Here it is important to not favor parameter choices that drains the short term storage system.

Also make believable that your fuel consumption is accurate. That is, explain where your design saves the most fuel and how this affects the total fuel consumption.

4.2 Available models and assumptions

First is a list of the available components you are allowed to add as well as common model assumptions and then a detailed walk through of some of the components.

- Flywheels
- Hydraulic Accumulators
- Supercapacitors

as well as the following *glue* components

- Gearboxes
- Electric motors
- Electric generators
- Continuously variable transmissions
- Hydraulic pumps/motors
- Torque couplers and planetary gear sets
- Power electronics

All short term storage devices should have the same, or higher, *charge status* after the driving cycle as before, otherwise this has to be accounted for in a realistic way.

4.2.1 Short term storage systems

The equations for the short term storage systems are specified in the course literature unless available here as a reference. Parameters are to be chosen within reasonable limitations. Investigate how different parameters (e.g. the speed of the flywheel, charge of the hydraulic accumulator or supercapacitor, and power) affect the efficiency of the component(s) used. This can e.g. be done using the Peukert or Ragone tests for the supercapacitor and hydraulic accumulator.

Flywheel

Assume that you are able to make flywheels using a material with $\rho = 8000$ [kg/m³] and are able to choose b , d and q freely within reasonable limits. Also assume that manufacturing limitations gives you the flywheel parameters in Table 4.1. Assume that the total weight of the flywheel and bearings is 5% more than the flywheel mass.

Parameter	Description	Value
ρ	Flywheel density	8000 [kg/m ³]
ρ_a	Ambient air density	1.29 [kg/m ³]
η_a	Dynamic air viscosity	$1.72 \cdot 10^{-5}$ [Pa s]
b	Width	By choice
d	Diameter	By choice
q	Inner/Outer diameter ratio	$q \in [0, 1]$
d_w/d	Shaft/Wheel ratio	0.08 [-]
μ	Friction coefficient	$1.5 \cdot 10^{-3}$ [-]
k	Unbalance factor	4 [-]
ω_{max}	Maximum speed	30 000 [rpm]
m_{tot}	Total mass	$1.05 \cdot m_f$

Table 4.1: Flywheel parameters from the flywheel manufacturer.

Hydraulic accumulator

Assume that the hydraulic accumulator may be described by a thermodynamic model together with the parameters in Table 4.2. Also assume that the total weight of the accumulator and its components are described by the equations for a spheric accumulator and that the weight of the metal shell is negligible. The weight of the oil should be at maximum charge. Note the importance of choosing the capacities so that the maximum pressure is never exceeded. It is

Parameter	Description	Value
$V_{g,max}$	Maximum gas capacity	By choice
$V_{g,min}$	Minimum gas capacity	By choice
f_c	Fluid capacity	By choice
ρ_{oil}	Hydraulic oil density	900 [kg/m ³]
T_w	Wall temperature	320 [K]
R_g	Gas constant	520 [J/kgK]
p_{max}	Maximum pressure	[400-800] [bar]
p_{init}	Pre charge pressure	125 [bar]
T_{init}	Pre charge temperature	320 [K]
h	Heat transfer coefficient	100 [W/Km ²]

Table 4.2: Hydraulic accumulator parameters from the manufacturer.

advantageous to look at the implementation details for the Supercapacitor from the QSS library during the implementation. Use the volume fraction as state of charge.

Supercapacitor

Use the equations from the equivalent circuit paragraph in the literature and the parameters in Table 4.3 below. You are free to use as many as necessary.

Parameter	Description	Value
C_{SC}	Capacity per supercap	8 [F]
R_{SC}	Internal resistance	0.72 [Ohm]
$V_{max,SC}$	Maximum voltage of supercap	225 [V]
$P_{max,SC}$	Maximum power drain of supercap	175 [kW]
E_{SC}	Specific energy of supercap	2 [Wh/kg]

Table 4.3: Model parameters and assumptions supercapacitor

4.2.2 Glue components

The equations for the *glue components* are specified in the course literature unless available here as a reference. Parameters are to be chosen within reasonable limitations unless specified.

Gearbox

The gearbox equations are

$$P_{out} = \eta_{GB} \cdot P_{in} - P_0$$
$$\omega_{in} = \omega_{out} \cdot i_x$$

where P_0 is the friction losses and is direction dependent. (See for example the gearbox implementation in the QSS library.) The model parameters are listed in Table 4.4.

Parameter	Description	Value
η_{GB}	Gearbox efficiency	0.98 [-]
P_0	Constant term in losses	50 [W]
m	Gearbox mass	10 [kg/gear]

Table 4.4: Model parameters and assumptions for a manual gearbox

Continuously variable transmission

Assume that the CVT can be described as a normal gearbox but with a lower efficiency and higher idling losses. Parameters are listed in Table 4.5.

Parameter	Description	Value
η_{GB}	Gearbox efficiency	0.93 [-]
P_0	Constant term in losses	400 [W]
m	Gearbox mass	10 [kg]

Table 4.5: Model parameters and assumptions for a CVT gearbox

In a CVT there is an upper limit in how fast the gear ratio can be changed, as well as a torque limit. However, these limitation are neglected in this task.

Hydraulic pump/motor

Use the Willans approach with the parameters in Table 4.6 below.

Parameter	Description	Value
P_0	Idling losses	300 [W]
e	Efficiency	0.8 [-]
m	Hydraulic pump mass	10 [kg]

Table 4.6: Model parameters and assumptions for hydraulic pump/motor

Torque coupler and planetary gear set

Assume that your torque couplers and or planetary gear sets are ideal without losses.

Power electronics

Neglect any power losses.

4.2.3 Energy converters

Electric motor

Assume that the electric motor is of the type from the QSS library. To help get you started the command *mkPlots.m* is available for download. The code shows how to plot engine performance maps and gives you an idea of how the efficiency of the electric motor in the QSS library is modeled. In Figure 4.1 the efficiency map for the electric motor has been plotted together with the torque limit. Assume that your engine is scalable using the scale parameter and the weight of the component and the power electronics is 1.5 kg/kW .

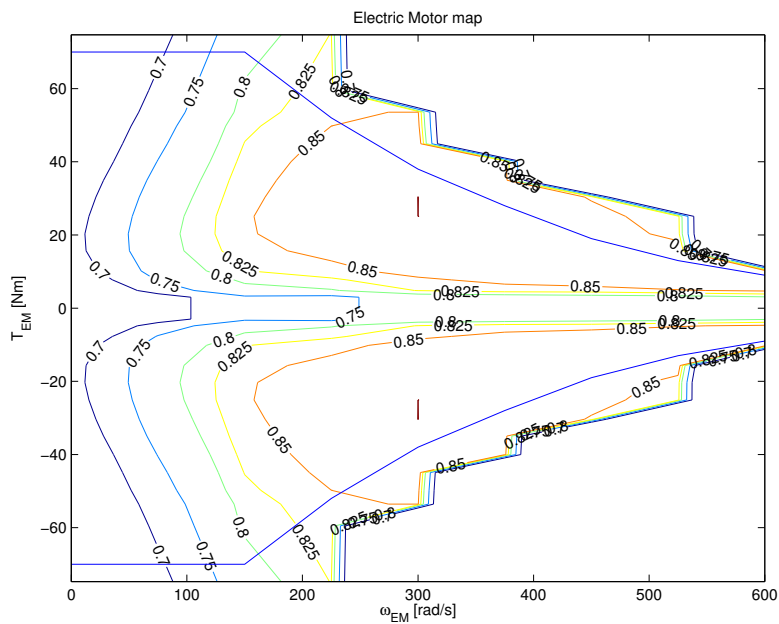


Figure 4.1: Performance map of electric motor from the QSS library

Electric generator

As with the electric motor assume that the electric generator is of the type from the QSS library. The command *mkPlots.m* is available for download to help you get started with plotting engine performance maps and get an idea of how the efficiency of the electric generator in the QSS library is implemented. In Figure 4.2 the efficiency map for the electric motor has been plotted together with the torque limit. Assume that the generator is scalable using the scale parameter and the weight of the component and power electronics is 1.5 kg/kW .

Combustion engine

A map based engine model is used in this task. The fuel consumption is tabulated and is estimated given the torque and speed of the engine. The parameters to be used are given in `OrdinaryVehicle.mdl`. If you change the size of the engine, approximate the change in weight to 1.2 kg/kW .

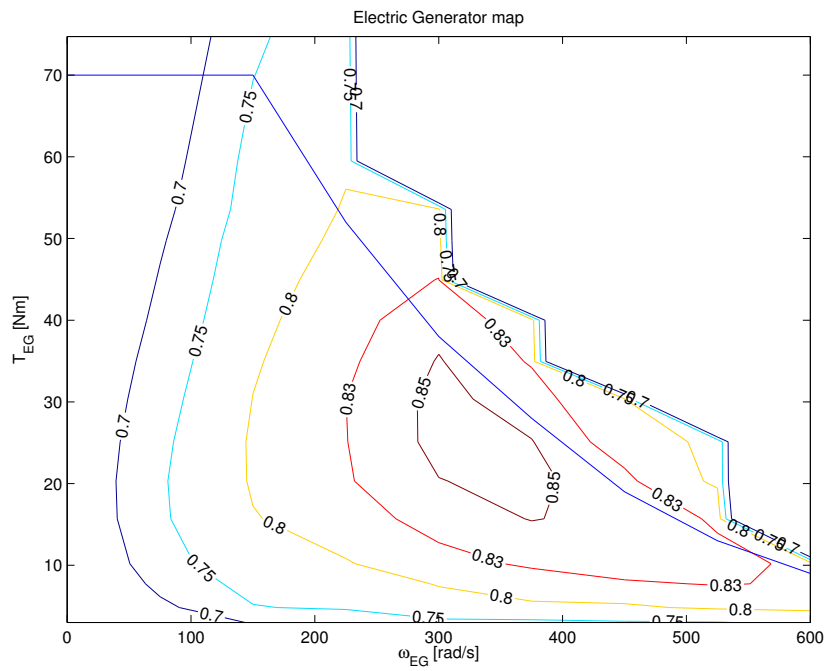


Figure 4.2: Performace map of electric generator from the QSS library

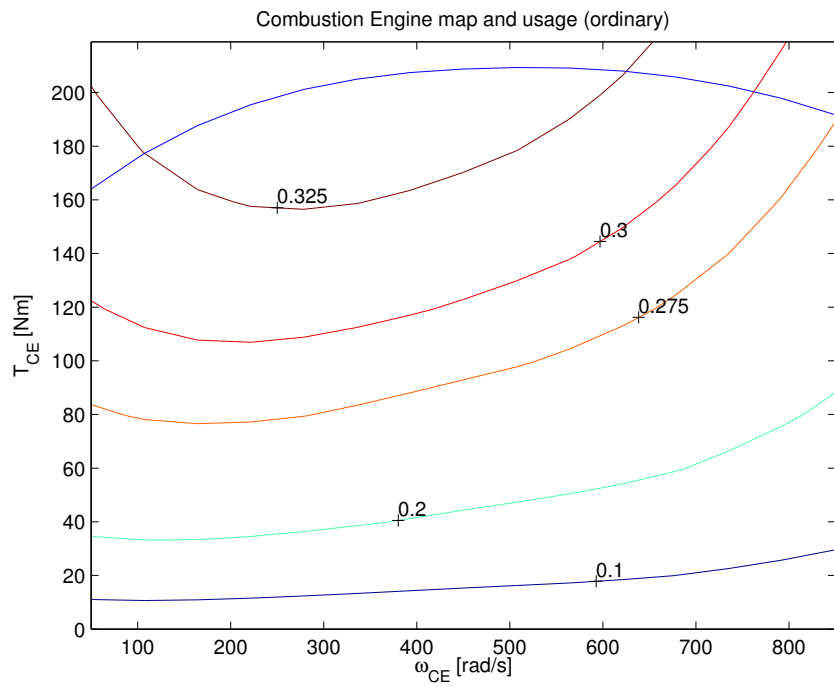


Figure 4.3: Performace map of combustion engine using the map based engine model

Projects 5

Fuel Cell and Supervisory Control

This project is not mandatory, but is an extra task that gives up to 14 points.

Purpose

In this project you are supposed to implement a fuel cell vehicle in Simulink using forward modeling. The purpose is twofold:

- get knowledge about how a fuel cell works and evaluate efficiencies and fuel consumption of a fuel cell vehicle.
- get familiar with forward modeling.

Examination requirement

- The vehicle should fulfill the specifications given in section [5.1.1](#).
- Calculate the fuel consumption using hydrogen as fuel. The fuel consumption is preferably presented in equivalent gasoline consumption per 100 km. Use NEDC.
- Calculate the fuel consumption if methanol is used as fuel instead of hydrogen, (use information in section [5.2.1](#)). Compare this result to a conventional vehicle equipped with an SI engine. Make the comparison in terms of both the energy consumption and CO₂ emissions.

Hint: To calculate the CO₂ emissions, assume stoichiometric mixture. Use the results from project 1 for the conventional vehicle.

- Calculate the average efficiency of the fuel cell, electric machine and the buffer.

5.1 Assignment specification

The assignment is to be solved using Simulink and a given model skeleton that can be downloaded from the course homepage. Chapter 6 in the Vehicle Propulsion System book [1] covers fuel cells. It might also be helpful to study the model implemented in QSS.

The final report must at least contain the following:

- Description and discussion of the design, including values of important parameters of your model.
- Description and discussion of your chosen control strategy.
- Plots showing the efficiency and operating points of your components.

The report should be self explanatory and all the components included in the model must be documented. All assumptions should be discussed and the control strategy should be well described, discussed, and motivated.

You should also evaluate and provide support for the credibility of your fuel consumption estimate. Furthermore, you should explain where your design saves the most fuel and how this affects the total fuel consumption.

5.1.1 Vehicle demands

To be able to compare the conventional vehicle to the vehicle developed in this assignment, the vehicle should manage to

- accelerate from stand still to 100 km/h in 15 s,
- have a sustained top speed of at least 160 km/h, and
- have high overall efficiency on the NEDC.

Vehicle and component parameters, such as the specific weights, are given in section 5.3.

5.1.2 Design of new vehicle

Write down the equations for all the components of the modeled vehicle. Then choose component sizes and other quantities. Make sure the vehicle fulfills the requirements in section 5.1.1. Finally plot the efficiencies (for the fuel cell, this could be efficiency against power), as well as limiting factors where applicable. Ensure that

1. all operating points will be within the limits for the used components,
2. the components will be operating close to the maximum efficiency when working together, and
3. the short term storage system[s] are large enough.

5.1.3 Design of control strategy

A control strategy with the same demands as described in section 4.1.3 is to be implemented.

5.2 Available models and assumptions

There are some models included in the skeleton that you can use. You are of course free to develop and add new models of the components. Skeletons for the controller and fuel cell are included in the given skeleton, which you are to add functionality to. Observe that the vehicle model is sensitive for naming of the signals, since buses are used. The parameters of the components are to be chosen in order to fulfill the requirements in section 5.1.1. You are free to choose any configuration of the vehicle you want to, as long as it is physically possible to construct. There is one concept of a fuel cell vehicle chosen in the given skeleton that you can use.

5.2.1 Fuel

You are supposed to implement a model of a vehicle that uses hydrogen as fuel, i.e. there is no reformer in the vehicle. This should result in a relatively high overall efficiency of the vehicle. The disadvantages associated with this technology are for example that hydrogen storage is problematic, new infrastructure is needed, and that transportation of hydrogen is costly.

An alternative is to use methanol as fuel and use a reformer on-board that produces hydrogen. Assume that the reformer has a mean efficiency of 55 %, and that the lower heating value of methanol is 19.8 MJ/kg.

5.3 Vehicle Data

In this section some data to be used in the modeling of the fuel cell vehicle is given. For the data not presented in this section, use the parameters for the sports car in project 1.

5.3.1 Fuel cell

The fuel cell has slower dynamics than for example an ICE. Therefore it is not adequate to assume that the requested power from the fuel cell is delivered instantaneously, if there is a change in the power demanded. In this task this is modeled using a first order low pass filter with a time constant of 5 seconds. Data needed for one cell in the stack is given in Table 5.1.

5.3.2 Super capacitor

A buffer consists of several cells connected in series and in some cases parallel. You are free to design the buffer as long as you use realistic parameters. The following data for a cell in the super capacitor is just an example of the magnitude of the parameters. The capacitance is 3 F, voltage 2.5 V and inner resistance 2 m Ω . The inner resistance is a relative large value. This is to model the losses due to leakage currents in the capacitor since that is not a part of the given model. If you wish to use other parameters <http://www.maxwell.com> is a good place to start looking.

Parameter	Description	Value
V_{th}	Theoretical voltage at $I_{fc} = 0$	1.3 [V]
V_0	Voltage at $I_{fc} = 0$ in linear approx.	0.88 [V]
A_{fc}	Fuel cell area	0.3 [m ²]
\bar{R}	Normalized resistance	0.00008 [Ω m ²]
λ	Air/fuel ratio	1.5 [-]
M_{air}	Molar mass of air	29.0 [kg/kmol]
$q_{thv,hydrogen}$	Lower heating value of hydrogen	285.9 MJ/kmol
η_{em}	Efficiency of em driving compressor	0.75 [-]
η_{comp}	Efficiency of compressor	0.70 [-]
Π	Compression ratio	1.3 [-]
P_{idle}	Minimum power from fuel cell stack	1000 [W]
T_{amb}	Ambient temperature	298 [K]

Table 5.1: Model parameters for one fuel cell. Use the data to model a stack.

5.3.3 Electric machine

You are free to model the electric machine in any way that you prefer, as long as it is realistic and you describe the model. If you use the model given in the skeleton, the data presented in table 5.2 might be useful.

Parameter	Description	Value
R	Inner resistance	0.35 [Ω]
J	Inertia	0.2 [kgm ²]
k_a	Torque constant	0.50 [Nm/A]
k_i	voltage/speed constant	0.51 [Vs/rad]

Table 5.2: Model parameters for the electric machine using the model *electric-motor-quasistatic2_std*.

In this model the power electronics is included converting the voltage of the buffer to the requested voltage of the electric machine.

5.3.4 Vehicle mass

The mass of the vehicle depends on the design of the components used. To be able to estimate the mass of the vehicle, the following information is to be used:

- the vehicle body weight 900 kg including a pay-load of 100 kg,
- the fuel cell weight 2 kg/kW where the power is the peak power of the fuel cell.
- The electric system including e.g. electric machine and power electronics has a mass of 1.5 kg/kW and
- the specific power of the super capacitor is 10 kW/kg and the specific energy 4 Wh/kg. In this task the weight of the super capacitor is assumed to be the maximum value of the two ways of estimating the weight.

You are free to use a battery instead of the super capacitor. If you do so you have to find information about the weight of the battery used in the modeled vehicle.

Bibliography

- [1] Lino Guzzella and Antoni Sciarretta. *Vehicle Propulsion Systems – Introduction to Modeling and Optimization*. Springer Verlag, 3 edition, 2013.