Lab Module #2

ECMS

Center for
Automotive Research
and Sustainable Mobility

Course schedule

Mon	Tue	Wed	Thu	Fri	Sat	Sun	
24	25	26	27	28	1	2	March
3	4	5	6	7	8	9	
10	11	12	13	14	15	16	
17	18	19	20	21	22	23	
24	25	26	27	28	29	30	
31	1	2	3	4	5	6	April
7	8	9	10	11	12	13	
14	15	16	17	18	19	20	
21	22	23	24	25	26	27	
28	29	30	1	2	3	4	May
5	6	7	8	9	10	11	
12	13	14	15	16	17	18	
19	20	21	22	23	24	25	
26	27	28	29	30	31	1	June
2	3	4	5	6	7	8	
9	10	11	12	13	14	15	

Lab 1

Lab 2

Lab 3

Lab 4

Lecture

Lab report due

Class hours

Monday

11:30 - 14:30, Room 04AM

Thursday

Class A: 10:00 - 11:30, Room 02AM

Class B: 11:30 - 13:00, Room 02AM

Tuesday, April 29th

To be confirmed

Contacts

Lectures & lead instructor

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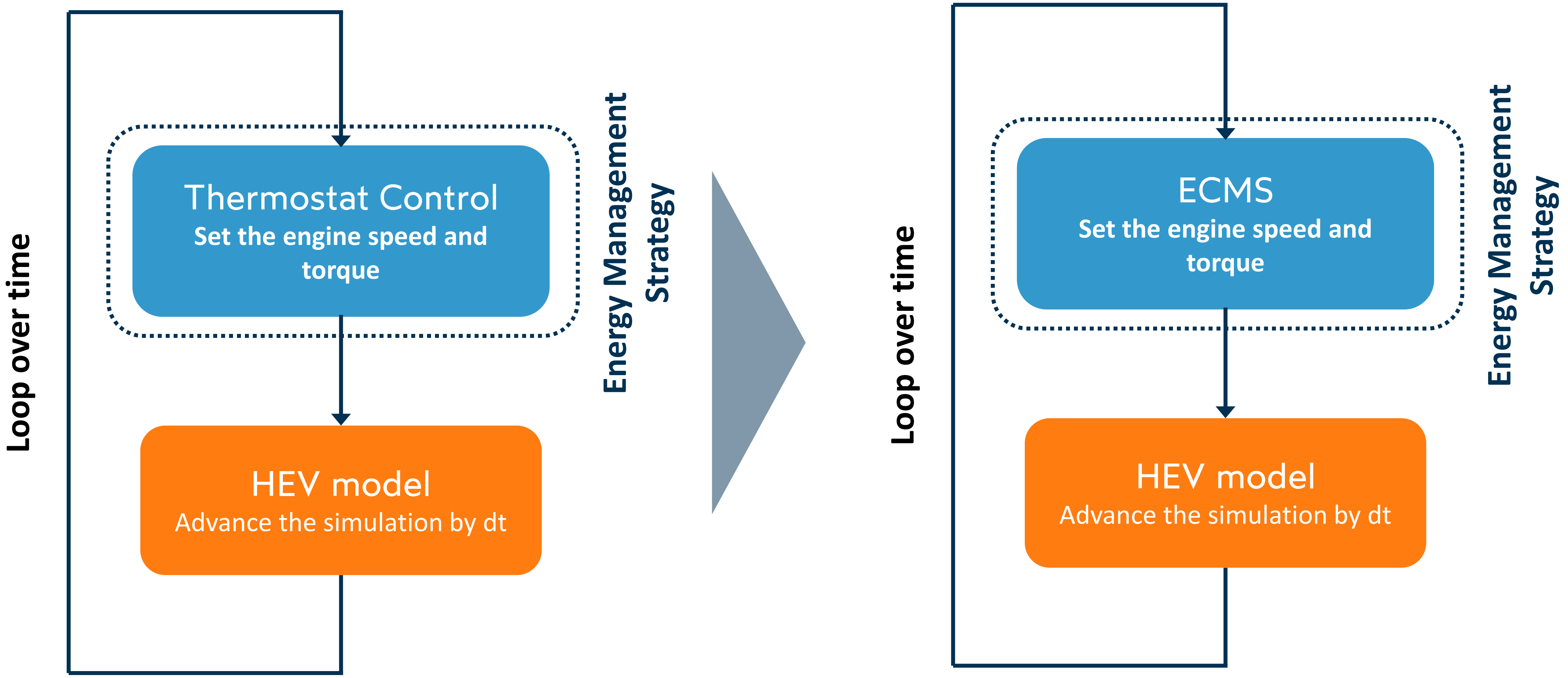
Lab Class A

Teacher: Federico Miretti federico.miretti@polito.it

Lab Class B

Teacher: Trentalessandro Costantino trentalessandro.costantino@polito.it

Simulation framework



Minimal simulation code:

$$\text{vehicleData} \leftarrow \text{load vehicleData}$$

$$v_{\text{veh}}, a_{\text{veh}} \leftarrow \text{load cycleData}$$

$$\text{for } k \text{ from 1 to } N$$

$$\omega_{\text{eng}}(k), T_{\text{eng}}(k) \leftarrow \text{ecmsControl}(\dots)$$

$$\sigma(k+1), \dot{m}_{\text{f}}(k) \leftarrow \text{hevModel}\left(\sigma(k), \left[\omega_{\text{eng}}(k), T_{\text{eng}}(k)\right], \left[v_{\text{veh}}(k), a_{\text{veh}}(k)\right], \text{hevData}\right)$$

$$\text{end for}$$

Basic ECMS controller

For all t in $[t_0, t_\mathrm{f}]$, select the γ and τ_eng that minimize:

$$\dot{m}_\mathrm{f,eq} = \dot{m}_\mathrm{f}(\omega_\mathrm{eng}, T_\mathrm{eng}) + p \cdot \dot{\sigma}(\omega_\mathrm{eng}, T_\mathrm{eng})$$

Costate

ECMS principle

Basic ECMS controller

For all t in $[t_0, t_\mathrm{f}]$, select the γ and τ_eng that minimize:

$$\dot{m}_\mathrm{f,eq} = \dot{m}_\mathrm{f}(\omega_\mathrm{eng}, T_\mathrm{eng}) + s \cdot \frac{E_\mathrm{b}}{Q_\mathrm{LHV}} \cdot \dot{\sigma}(\omega_\mathrm{eng}, T_\mathrm{eng})$$

Equivalence factor

Notation

- *Costate* is a term that is borrowed from optimal control theory.
- *Equivalence factor* is a more specific term used in the context of the ECMS.

Sometimes, the terms are used interchangeably.

Basic ECMS controller

For all t in $[t_0, t_f]$, select the γ and τ_{eng} that minimize:

$$\dot{m}_{\text{f,eq}} = \dot{m}_{\text{f}}(\omega_{\text{eng}}, T_{\text{eng}}) + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}(\omega_{\text{eng}}, T_{\text{eng}})$$

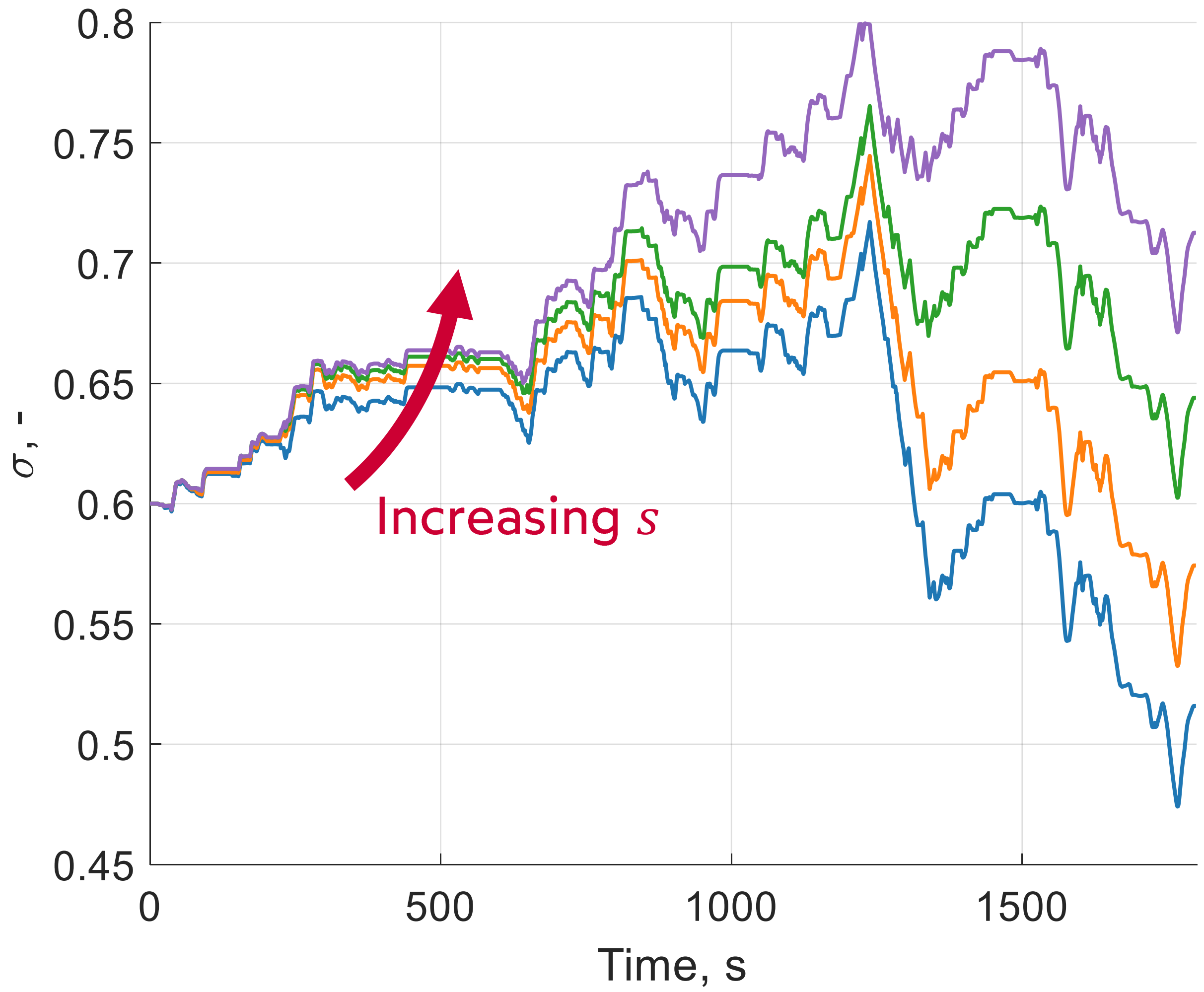
i.e.

$$(\omega_{\text{eng}}, T_{\text{eng}}) = \underset{\gamma, \alpha_{\text{eng}}}{\operatorname{argmin}} \left\{ \dot{m}_{\text{f}}(\omega_{\text{eng}}, T_{\text{eng}}) + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}(\omega_{\text{eng}}, T_{\text{eng}}) \right\}$$

Notation

- *Costate* is a term that is borrowed from optimal control theory.
- *Equivalence factor* is a more specific term used in the context of the ECMS.

Sometimes, the terms are used interchangeably.



Equivalence factor

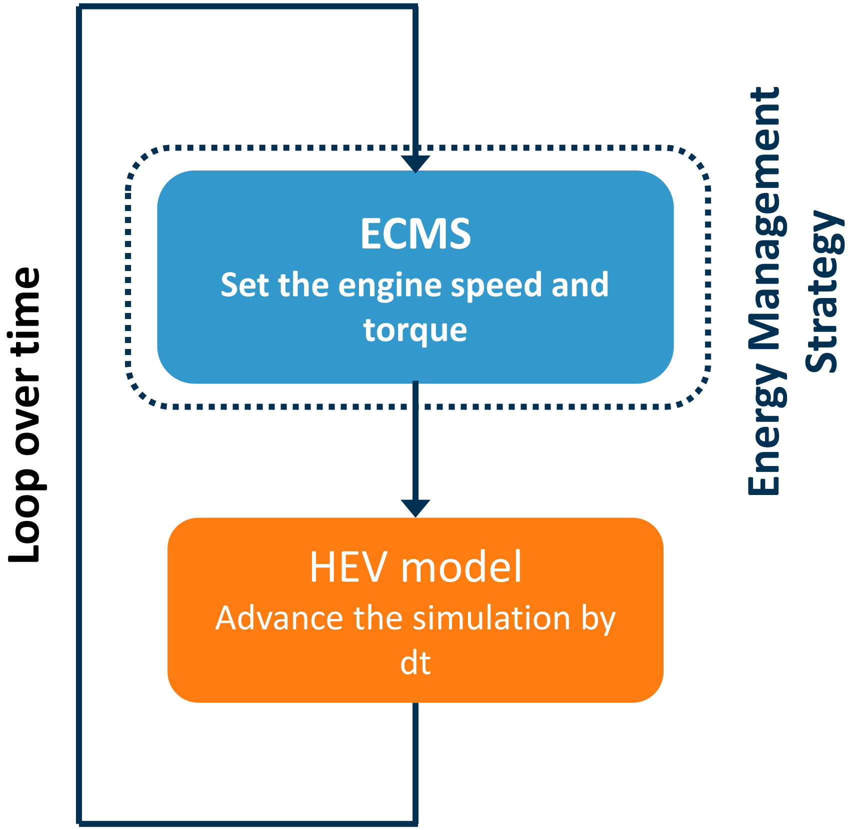
We will use a constant equivalence factor.

We will calibrate the equivalence factor to enforce:

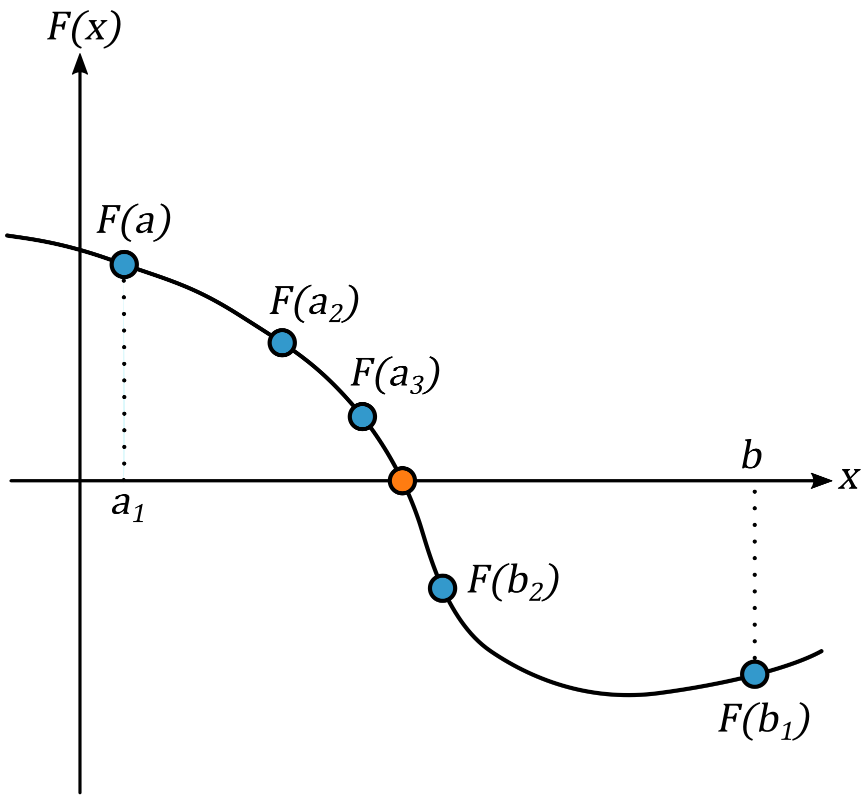
$$\sigma_f = \sigma_0$$

by developing a *bisection* algorithm.

1. Design the ECMS controller



2. Calibrate the equivalence factor with a bisection algo



Basic ECMS controller

We are at a fixed time t.

Select the ω_{eng} and T_{eng} that minimize:

$$\dot{m}_{\text{f,eq}} = \dot{m}_{\text{f}}(\omega_{\text{eng}}, T_{\text{eng}}) + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}(\omega_{\text{eng}}, T_{\text{eng}})$$

i.e.

$$(\omega_{\text{eng}}, T_{\text{eng}}) = \underset{\gamma, \alpha_{\text{eng}}}{\operatorname{argmin}} \{\dot{m}_{\text{f,eq}}(\gamma, \alpha_{\text{eng}})\}$$

Equivalence factor:

At this stage, assume s is known and given to the ECMS controller as input. Use a random guess. Do not worry about charge sustenance.

ECMS: practical implementation

Basic ECMS controller

We are at a fixed time t.

Select the ω_{eng} and T_{eng} that minimize:

$$\dot{m}_{\text{f,eq}} = \dot{m}_{\text{f}}(\omega_{\text{eng}}, T_{\text{eng}}) + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}(\omega_{\text{eng}}, T_{\text{eng}})$$

i.e.

$$(\omega_{\text{eng}}, T_{\text{eng}}) = \underset{\gamma, \alpha_{\text{eng}}}{\operatorname{argmin}} \{\dot{m}_{\text{f,eq}}(\gamma, \alpha_{\text{eng}})\}$$

Algorithm outline:

1. Evaluate $\dot{m}_{\text{f,eq}}$ for all possible $\omega_{\text{eng}}, T_{\text{eng}}$ combinations.
2. Exclude the unfeasible combinations.
3. Select the combination that minimizes $\dot{m}_{\text{f,eq}}$.

You must create a set of possible $\omega_{\text{eng}}, T_{\text{eng}}$ values.

ECMS: practical implementation

$\omega_{\text{eng, set}} \leftarrow$ create the set of possible ω_{eng} values

$T_{\text{eng, set}} \leftarrow$ create a set of possible T_{eng} values

for all $(\omega_{\text{eng}}, T_{\text{eng}})$ in $(\omega_{\text{eng, set}}, T_{\text{eng, set}})$

$\sigma_{k+1}, \dot{m}_{\text{f}} \leftarrow \text{hevModel}(\sigma_k, [\omega_{\text{eng}}, T_{\text{eng}}], [v_{\text{veh},k}, a_{\text{veh},k}])$

End

$$\dot{m}_{\text{f,eq}} \leftarrow \dot{m}_{\text{f}} + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}$$

$$\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*} \leftarrow \underset{\omega_{\text{eng}}, T_{\text{eng}}}{\text{argmin}}\ \dot{m}_{\text{f,eq}}$$

return $\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*}$

Algorithm outline:

1. Evaluate $\dot{m}_{\text{f,eq}}$ for all possible $\omega_{\text{eng}}, T_{\text{eng}}$ combinations.
2. Exclude the unfeasible combinations.
3. Select the combination that minimizes $\dot{m}_{\text{f,eq}}$.

You must create a set of possible $\omega_{\text{eng}}, T_{\text{eng}}$ values.

Tips and thinking points

1. You must create a set of possible ω_{eng} and T_{eng} values. You may find `linspace` or `ndgrid` useful.

2. When evaluating $\dot{m}_{\mathrm{f,eq}}$, be careful with the units of measurement.

3. How do you store $\dot{m}_{\mathrm{f,eq}}\left(\omega_{\mathrm{eng}}, T_{\mathrm{eng}}\right)$ in practice?

4. Select the combination that minimizes $\dot{m}_{\mathrm{f,eq}}$: you will find it useful to read the docs for the `min` function.

5. You must exclude (penalize?) the unfeasible combinations.

6. You may (or may not) find it useful to read the docs for the `ind2sub` function.

ECMS: practical implementation

$\omega_{\text{eng, set}} \leftarrow$ create the set of possible ω_{eng} values

$T_{\text{eng, set}} \leftarrow$ create a set of possible T_{eng} values

for all $(\omega_{\text{eng}}, T_{\text{eng}})$ in $(\omega_{\text{eng, set}}, T_{\text{eng, set}})$

$\sigma_{k+1}, \dot{m}_{\text{f}} \leftarrow \text{hevModel}(\sigma_k, [\omega_{\text{eng}}, T_{\text{eng}}], [v_{\text{veh},k}, a_{\text{veh},k}])$

End

$$\dot{m}_{\text{f,eq}} \leftarrow \dot{m}_{\text{f}} + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}$$

$$\omega_{\text{eng}}{}^*, T_{\text{eng}}^* \leftarrow \underset{\omega_{\text{eng}}, T_{\text{eng}}}{\text{argmin}} \ \dot{m}_{\text{f,eq}}$$

return $\omega_{\text{eng}}{}^*, T_{\text{eng}}^*$

Storing $\dot{m}_{\text{f,eq}}$

- You can store σ_{k+1} in a matrix where rows correspond to different values of ω_{eng} and columns correspond to T_{eng}.
- The same goes for $\dot{m}_{\text{f}}$.
- As a result of the sum, $\dot{m}_{\text{f,eq}}$ will have the same shape and structure.

ECMS: practical implementation

$\omega_{\text{eng, set}} \leftarrow$ create the set of possible ω_{eng} values

$T_{\text{eng, set}} \leftarrow$ create a set of possible T_{eng} values

for all $(\omega_{\text{eng}}, T_{\text{eng}})$ in $(\omega_{\text{eng, set}}, T_{\text{eng, set}})$

$\quad \sigma_{k+1}, \dot{m}_{\text{f}} \leftarrow \text{hevModel}(\sigma_k, [\omega_{\text{eng}}, T_{\text{eng}}], [v_{\text{veh},k}, a_{\text{veh},k}])$

End

$$\dot{m}_{\text{f,eq}} \leftarrow \dot{m}_{\text{f}} + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}$$

$$\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*} \leftarrow \underset{\omega_{\text{eng}}, T_{\text{eng}}}{\text{argmin}} \; \dot{m}_{\text{f,eq}}$$

return $\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*}$

Finding $\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*}$

- Use the `min` function and return the second output.
- Note that you always get a *linear index*.

ECMS: practical implementation

$\omega_{\text{eng, set}} \leftarrow$ create the set of possible ω_{eng} values

$T_{\text{eng, set}} \leftarrow$ create a set of possible T_{eng} values

for all $(\omega_{\text{eng}}, T_{\text{eng}})$ in $(\omega_{\text{eng, set}}, T_{\text{eng, set}})$

$$\sigma_{k+1}, \dot{m}_{\text{f}} \leftarrow \text{hevModel}(\sigma_k, [\omega_{\text{eng}}, T_{\text{eng}}], [v_{\text{veh},k}, a_{\text{veh},k}])$$

End

$$\dot{m}_{\text{f,eq}} \leftarrow \dot{m}_{\text{f}} + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}$$

$$\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*} \leftarrow \underset{\omega_{\text{eng}}, T_{\text{eng}}}{\text{argmin}} \ \dot{m}_{\text{f,eq}}$$

return $\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*}$

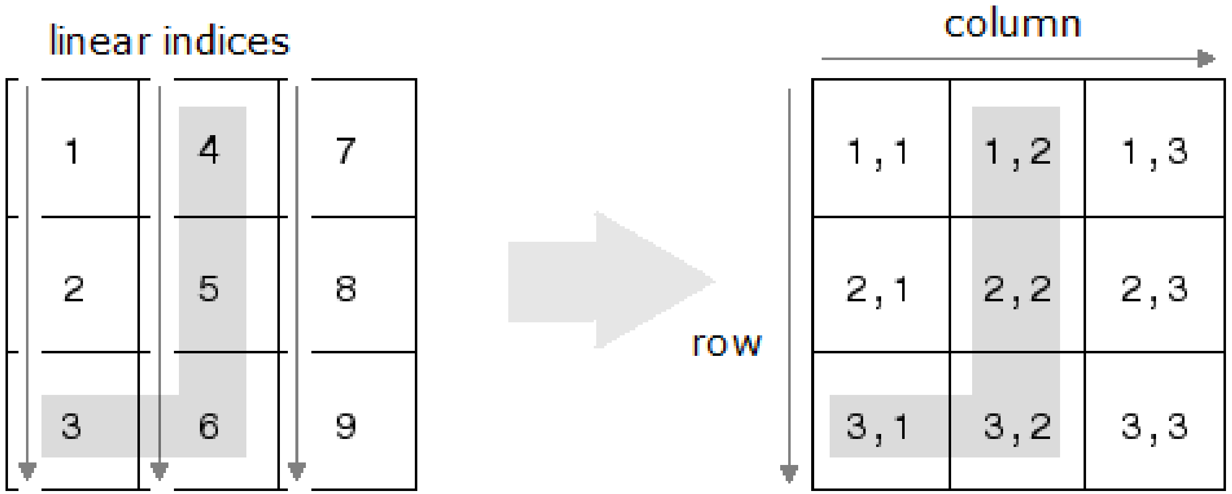
$\dot{m}_{\text{f,eq}}$	$T_{\text{eng, set}}$		
$\omega_{\text{eng, set}}$	(1,1)	(2,1)	(1,3)
	(2,1)	(2,2)	(2,3)
	(3,1)	(3,2)	(3,3)

Finding $\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*}$

- Use the `min` function and return the second output.
- Note that you always get a *linear index*.

ECMS: practical implementation

```
[min_val, idx] = min(A(:))
[min_val, idx] = min(A, [], 'all')
```




```
[row,col] = ind2sub(size(A), idx)
```

Finding $\omega_{\text{eng}}{}^{*}, T_{\text{eng}}^{*}$

- Use the `min` function and return the second output.
- Note that you always get a *linear index*.
- If needed, you can use `ind2sub` to get row and column subscript from a linear index. (*Note: this is not necessarily the most time-efficient option.*)

ECMS: practical implementation

$\omega_{\text{eng, set}} \leftarrow$ create the set of possible ω_{eng} values

$T_{\text{eng, set}} \leftarrow$ create a set of possible T_{eng} values

for all $(\omega_{\text{eng}}, T_{\text{eng}})$ in $(\omega_{\text{eng, set}}, T_{\text{eng, set}})$

$\sigma_{k+1}, \dot{m}_{\text{f}}, \text{unfeas} \leftarrow \text{hevModel}(\sigma_k, [\omega_{\text{eng}}, T_{\text{eng}}], [v_{\text{veh},k}, a_{\text{veh},k}])$

End

$$\dot{m}_{\text{f,eq}} \leftarrow \dot{m}_{\text{f}} + s \cdot \frac{E_{\text{b}}}{Q_{\text{LHV}}} \cdot \dot{\sigma}$$

$$\dot{m}_{\text{f,eq}}(\text{unfeas} == \text{True}) \leftarrow \dot{m}_{\text{f,eq}}(\text{unfeas} == \text{True}) + \text{penalty}$$

$$\omega_{\text{eng}}^*, T_{\text{eng}}^* \leftarrow \underset{\omega_{\text{eng}}, T_{\text{eng}}}{\text{argmin}}\ \dot{m}_{\text{f,eq}}$$

return $\omega_{\text{eng}}^*, T_{\text{eng}}^*$

Excluding unfeasible controls

- You have to make sure you exclude unfeasible controls!
- Add a high penalty to $\dot{m}_{\text{f,eq}}$ for the $(\omega_{\text{eng}}, T_{\text{eng}})$ combinations for which unfeas is true.