EMR'25, Lille (France)

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« EMR-based Model of a hybrid braking for BEV»

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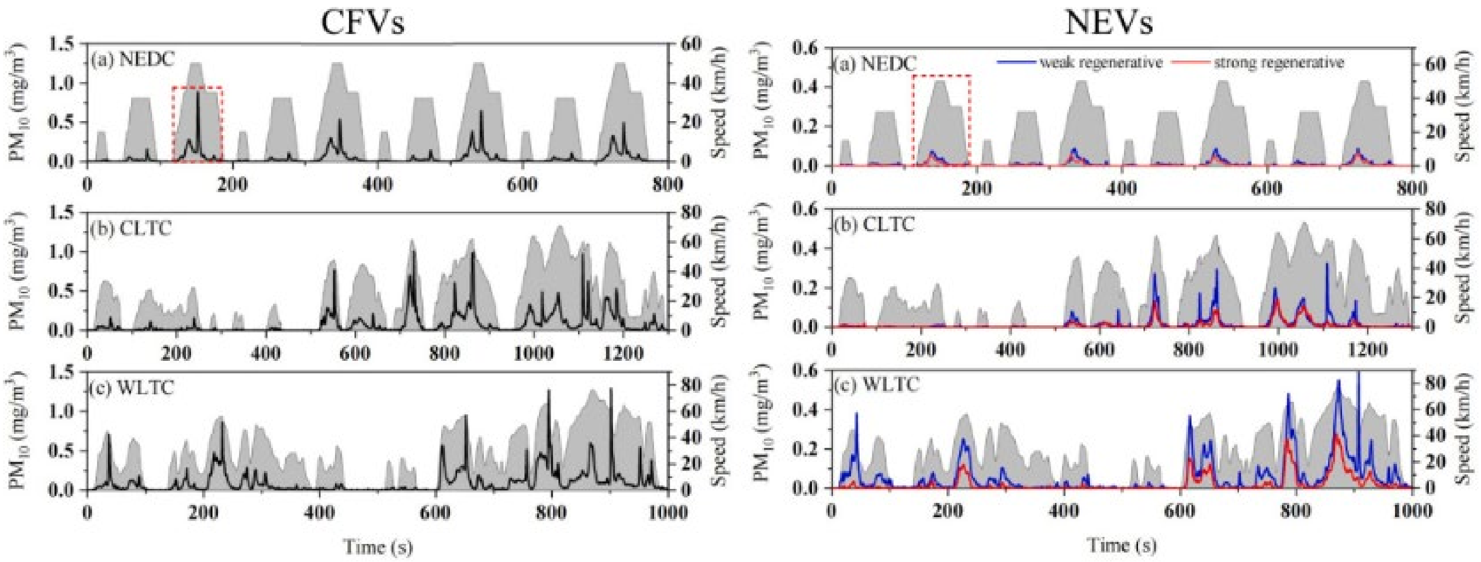
- Outline -

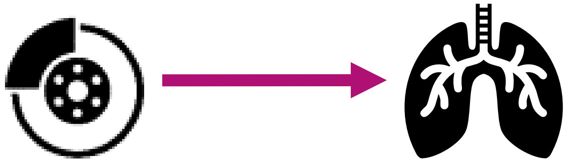
1. Importance of brakes modelling in traction model
2. Heat equation and application to brakes
3. Brakes temperature estimation in EMR-based model

«Importance of brakes modelling in traction model»

Non-exhaust emissions of a vehicle – brakes case



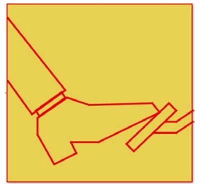
Mass concentration emission characteristics of BWP from CFVs and NEVs under standard test cycle [Zhang 2024]



- Using mechanical braking leads to pollutants emissions such as noise and fine particles
- Security norms impose the usage of mechanical brakes
- Not using enough mechanical brakes may leads to instabilities

Brake-by-wire and electrical braking

Braking pedal



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Numerical controller

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Electrical braking

Mechanical braking

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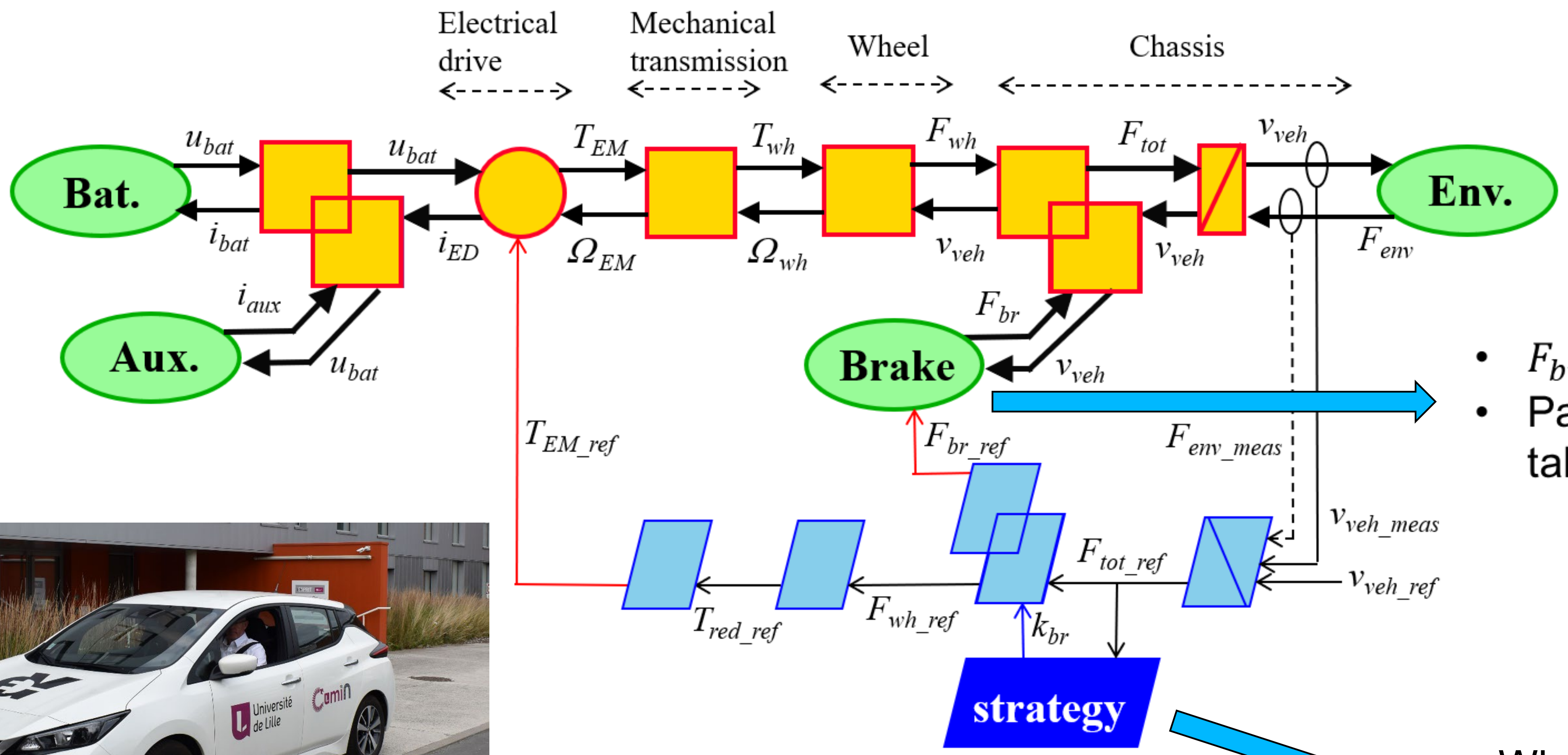
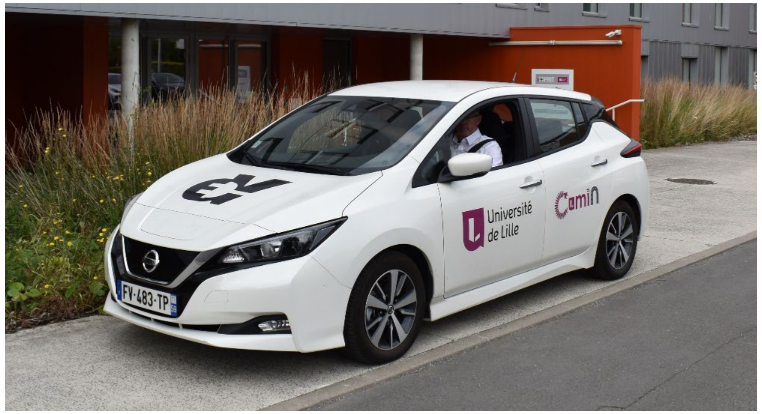
Battery charging

Pollution emission: fine particles, noise, and vibrations

CURRENT MODEL AND CONTROL

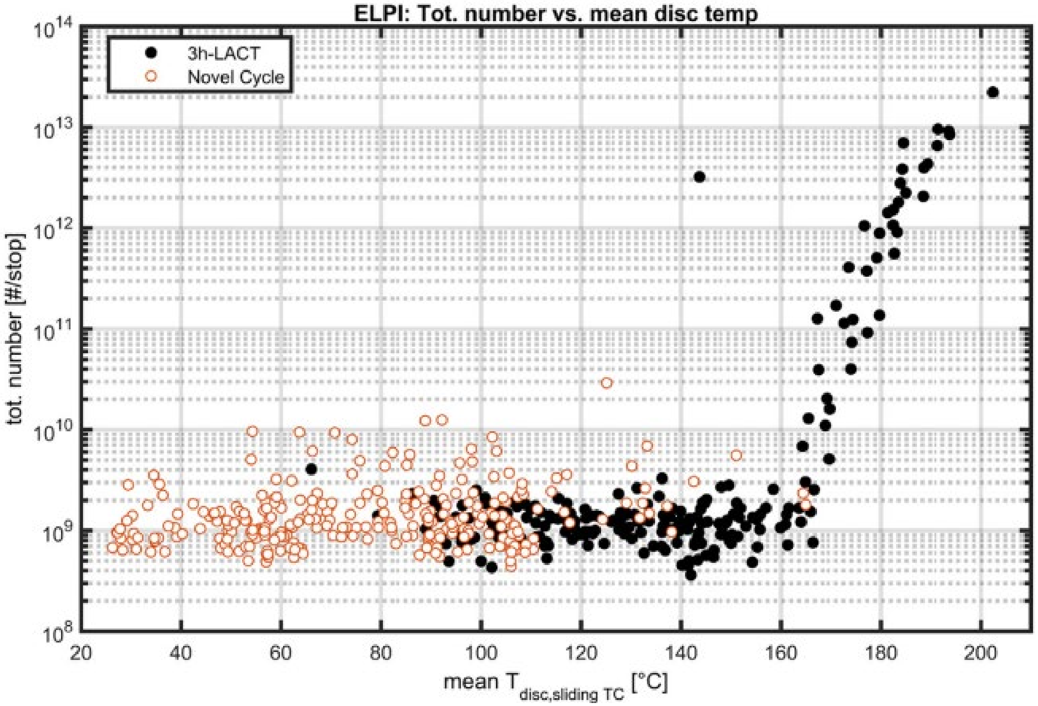


- $F_{br} = F_{br\_ref}$
- Particle emissions not taken into account



What braking strategy for the BEV?

Brakes temperature and particle emissions



Particle [6nm-10µm] number emissions and average disc temperature for several driving cycles [Mathissen 2018]

High temperature => high particles emissions
AND more ultrafine particles emissions

Need to estimate brakes temperature

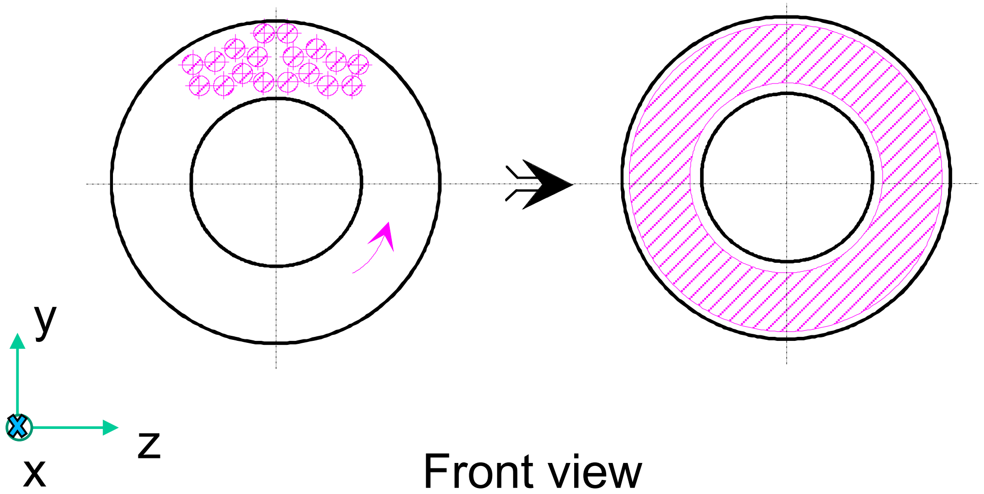
«Heat equation and application to brakes»

Assumptions of the thermal model studied

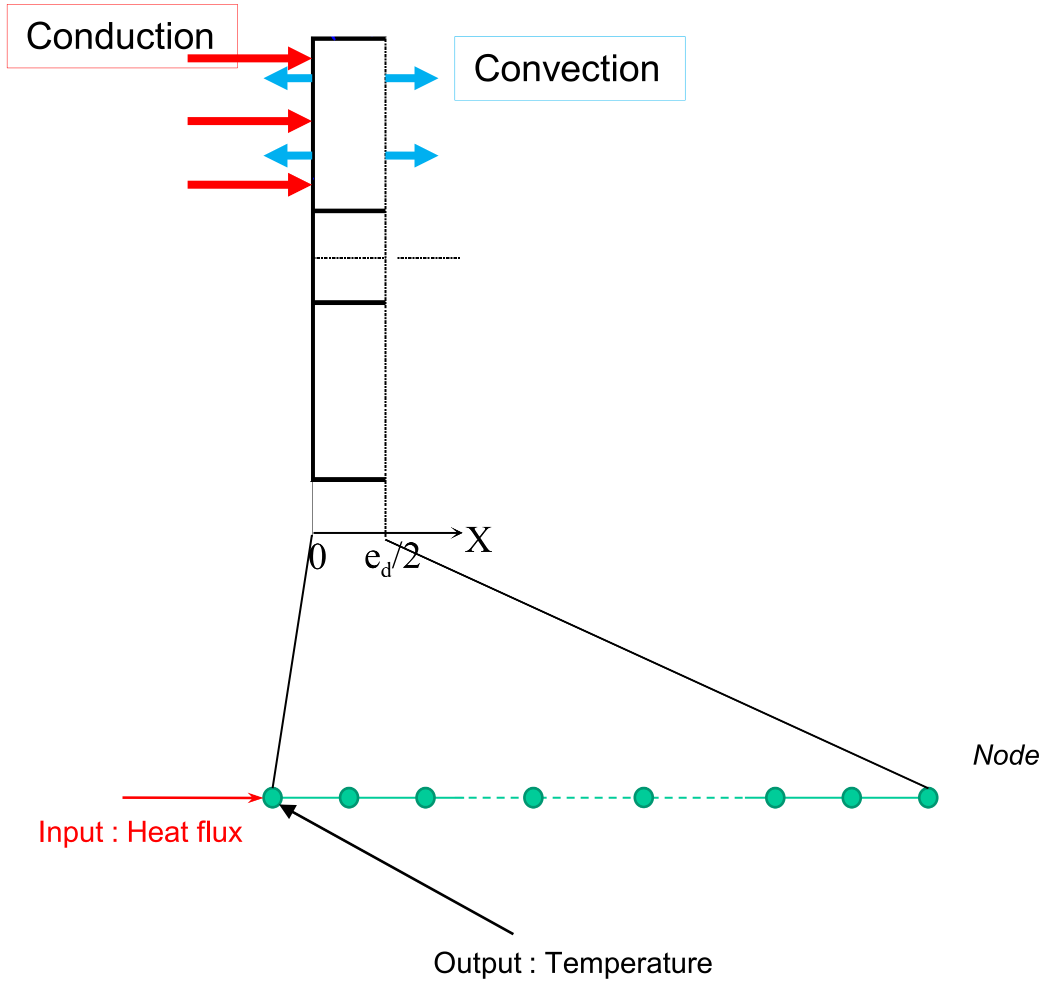
Assumptions :

- Only thermal flux on the disk (not on the pad)
- Only half of the disk studied (symmetry)

- Heat is distributed over the entire surface of the disc during braking
- Thermal flux in only one direction



Front view



Side view

Heat equation

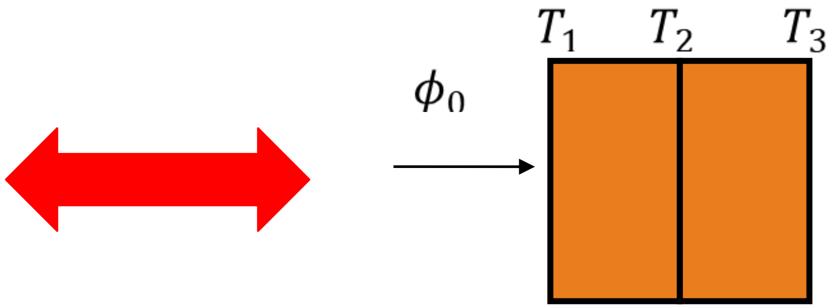
$$\rho c \frac{dT}{dt} - \lambda \Delta T = \phi_{cduct} + \phi_{cvect}$$

Conduction during contact between pads and the disk => **heating**

Convection with the air => **cooling**

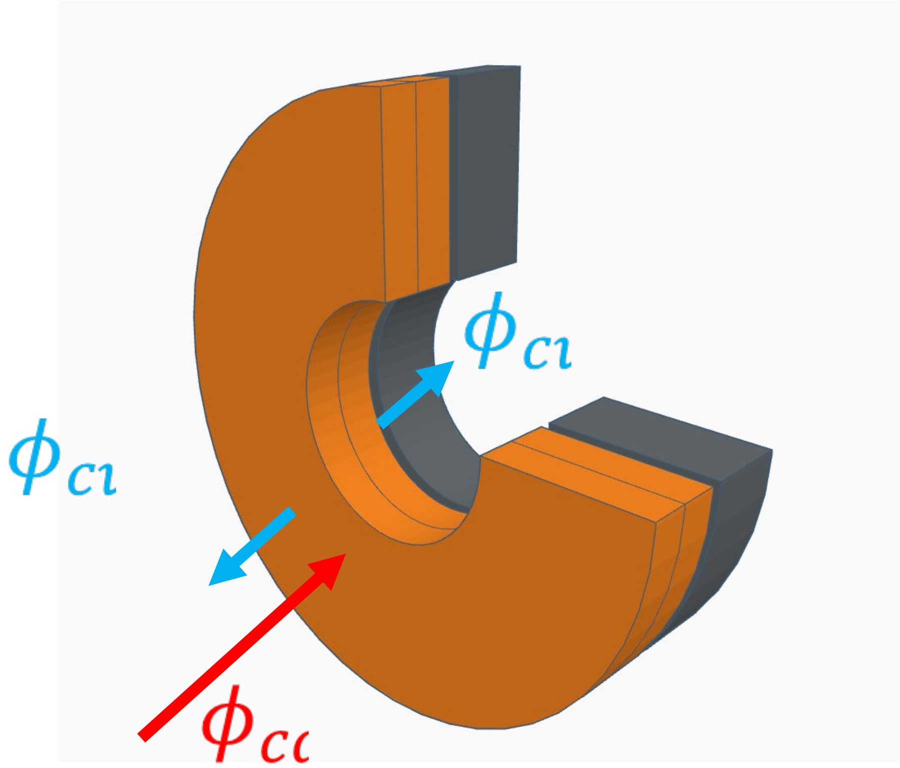
- Significant temperature rise at the surface, but slower heating of the overall disk
- Impossible to consider an average brake temperature

Simple mesh for the study



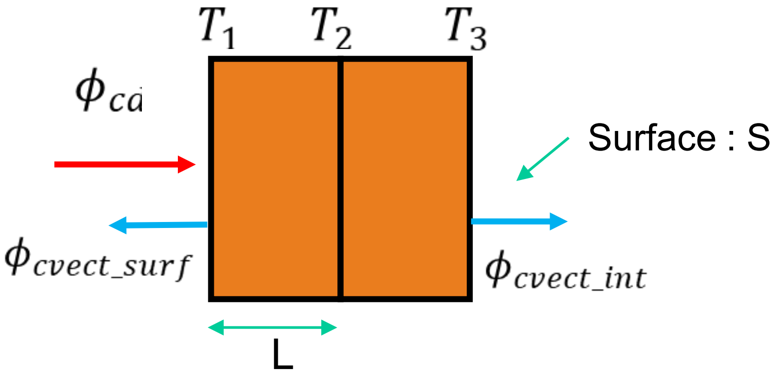
Study of the problem for a simple mesh – convection neglected

Study of the problem for a simple mesh – convection considered



Conduction effect

$$\phi_{cduct} = F_{T\_gr} v_{veh}$$



Law of Fourrier :

$$\phi_{1\to2} = -\lambda grad(T) = -\lambda S \frac{T_2 - T_1}{L} = \frac{T_2 - T_1}{R_{th}}$$

First law of thermodynamics : $dE = \underbrace{\rho c S L}_{C_{th}} dT = (\phi_{incoming} - \phi_{outgoing})dt$

$$\begin{pmatrix} C_{th} & 0 & 0 \\ 0 & C_{th} & 0 \\ 0 & 0 & C_{th} \end{pmatrix} \begin{pmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \\ \frac{dT_3}{dt} \end{pmatrix} + \begin{pmatrix} \frac{1}{R_{th}} & -\frac{1}{R_{th}} & 0 \\ -\frac{1}{R_{th}} & \frac{2}{R_{th}} & -\frac{1}{R_{th}} \\ 0 & -\frac{1}{R_{th}} & \frac{1}{R_{th}} \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} \phi_{cduct} \\ 0 \\ 0 \end{pmatrix}$$

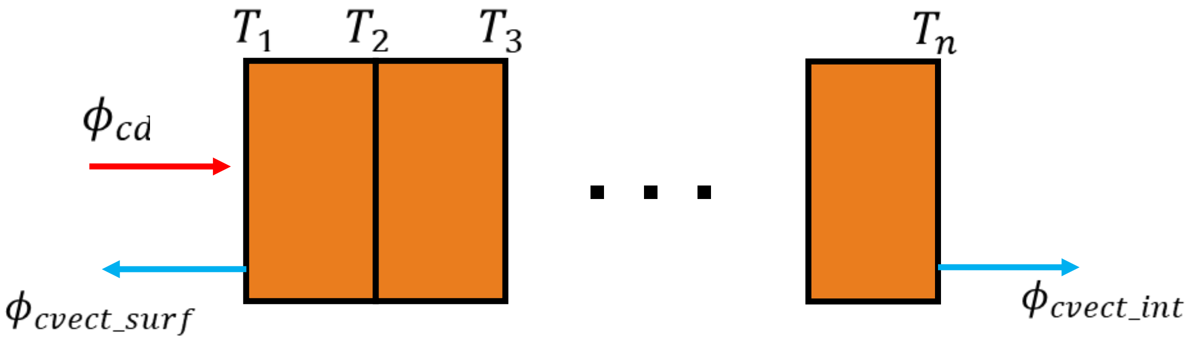
$$\begin{pmatrix} C_{th} & 0 & 0 \\ 0 & C_{th} & 0 \\ 0 & 0 & C_{th} \end{pmatrix} \begin{pmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \\ \frac{dT_3}{dt} \end{pmatrix} + \begin{pmatrix} \frac{1}{R_{th}} + hS & -\frac{1}{R_{th}} & 0 \\ -\frac{1}{R_{th}} & \frac{2}{R_{th}} & -\frac{1}{R_{th}} \\ 0 & -\frac{1}{R_{th}} & \frac{1}{R_{th}} + hS \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} \phi_{cduct} + hST_{ext} \\ 0 \\ hST_{ext} \end{pmatrix}$$

Convection effect

$$\phi_{cvect\_surf} = hS(T_1 - T_{ext})$$

$$\phi_{cvect\_int} = hS(T_3 - T_{ext})$$

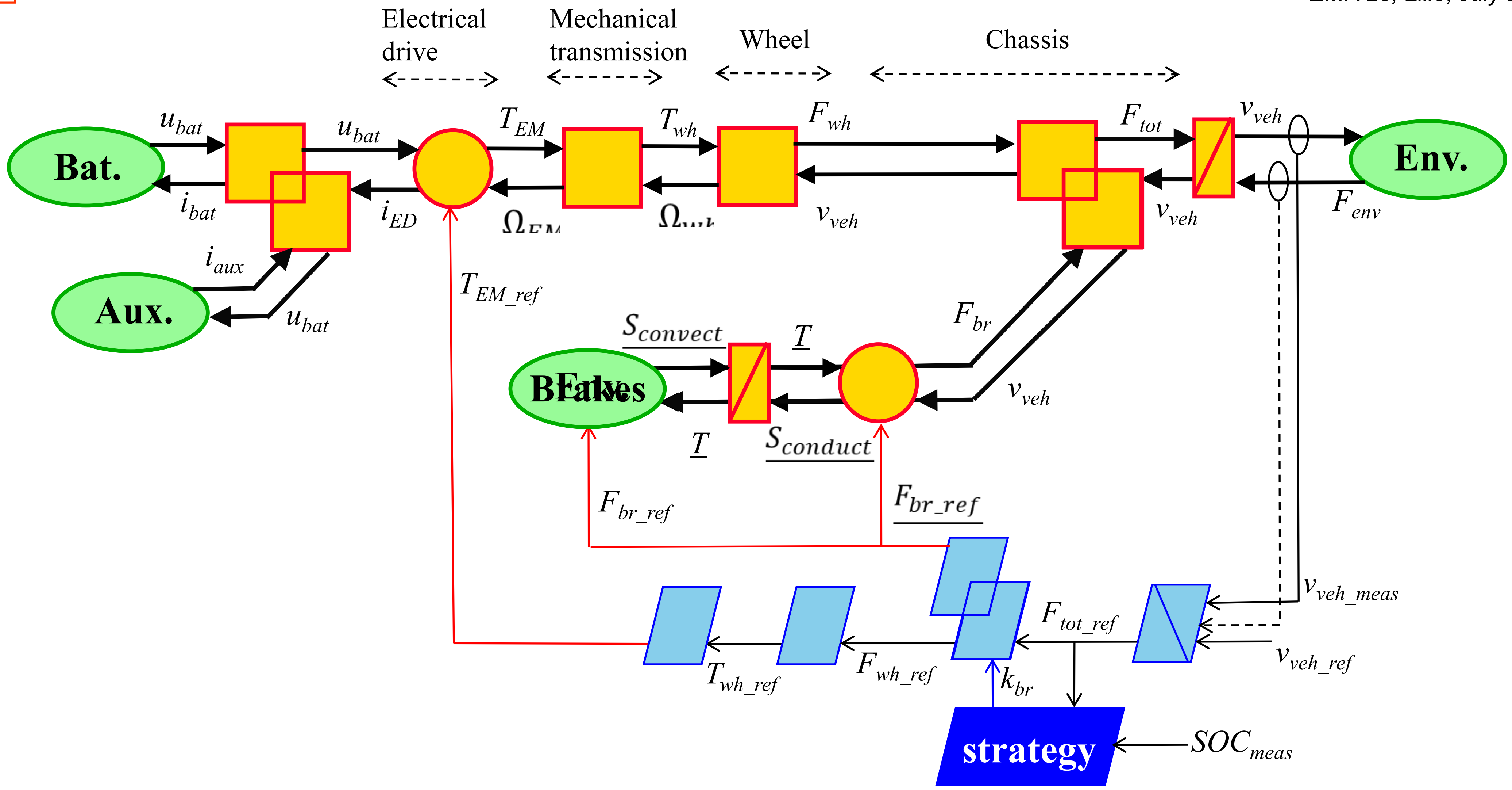
Complexification of the mesh



$$
\underbrace{\begin{bmatrix} C_{th} & 0 & \cdots & 0 \\ 0 & C_{th} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & C_{th} \end{bmatrix}}_{[(}
\underbrace{\begin{bmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \\ \frac{dT_3}{dt} \\ \vdots \\ \frac{dT_n}{dt} \end{bmatrix}}_{\frac{d}{d}}
+
\underbrace{\begin{bmatrix} \frac{1}{R_{th}}+hS & -\frac{1}{R_{th}} & 0 & \cdots & 0 & 0 & 0 \\ -\frac{1}{R_{th}} & \frac{2}{R_{th}} & -\frac{1}{R_{th}} & \cdots & 0 & 0 & 0 \\ 0 & -\frac{1}{R_{th}} & \frac{2}{R_{th}} & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & \frac{2}{R_{th}} & -\frac{1}{R_{th}} & 0 \\ 0 & 0 & 0 & \cdots & -\frac{1}{R_{th}} & \frac{2}{R_{th}} & -\frac{1}{R_{th}} \\ 0 & 0 & 0 & \cdots & 0 & -\frac{1}{R_{th}} & \frac{1}{R_{th}}+hS \end{bmatrix}}_{[(}
\underbrace{\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_n \end{bmatrix}}_{\underline{T}}
=
\underbrace{\begin{bmatrix} \phi_{cduct}+hST_{ext} \\ 0 \\ 0 \\ \vdots \\ hST_{ext} \end{bmatrix}}_{\underline{\Phi}}
$$

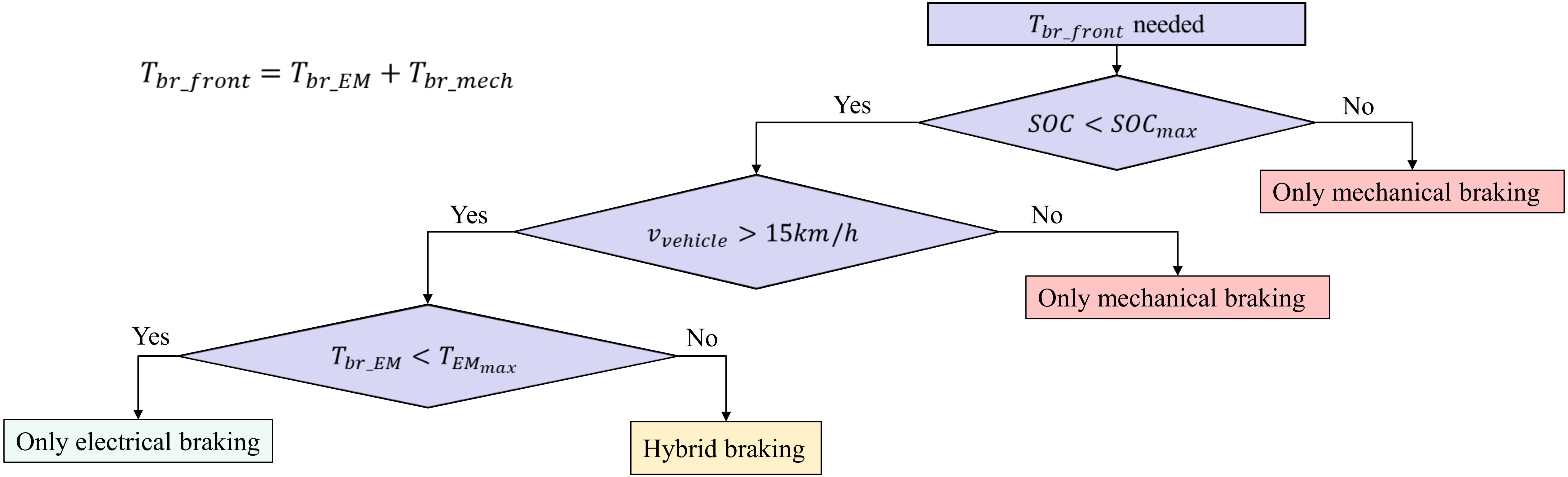
«Brakes temperature estimation in EMR-based model»

EMR representation



Simple distribution strategy for mechanical and electrical braking on front brakes

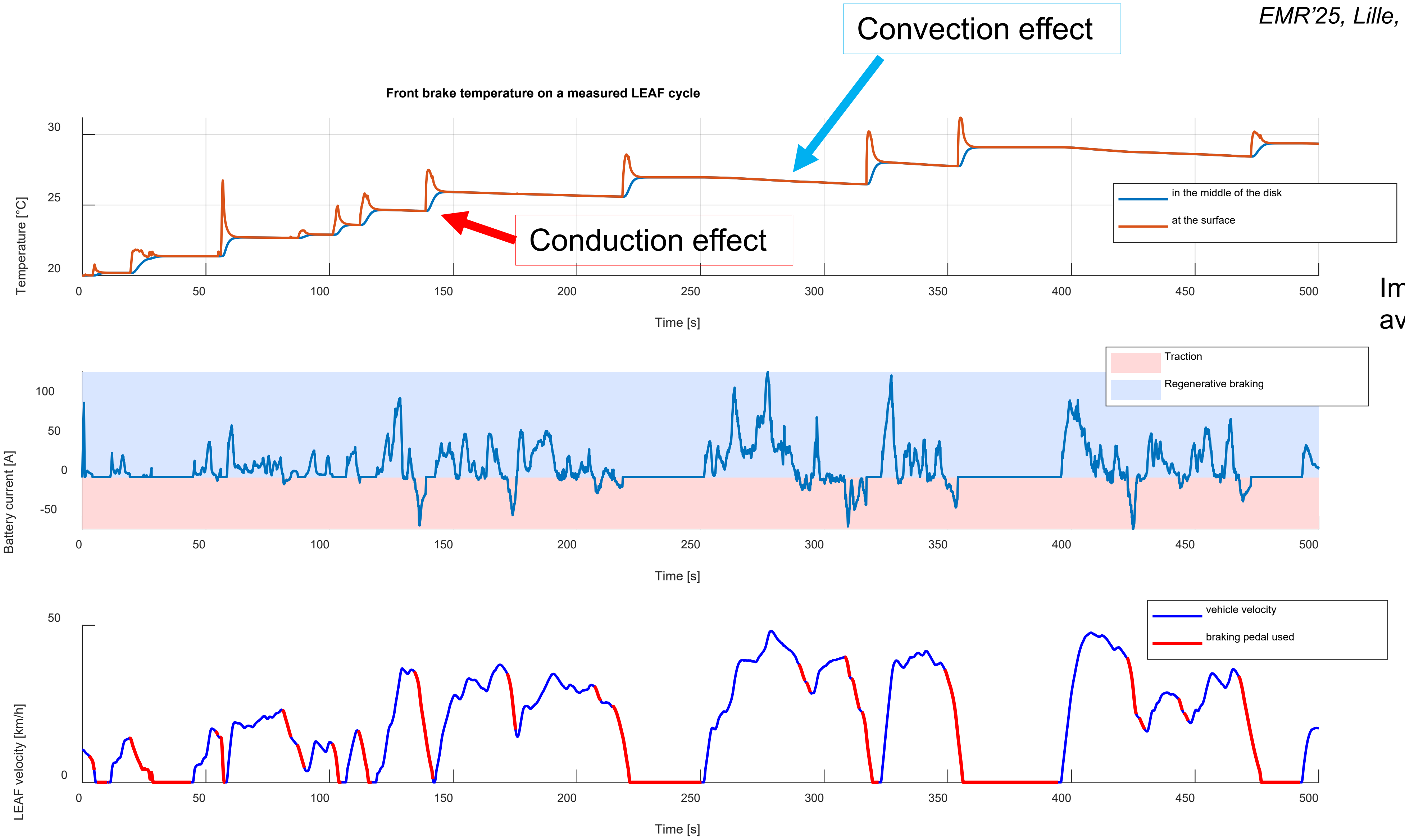
$$T_{br\_front} = T_{br\_EM} + T_{br\_mech}$$



« As much electrical braking as possible »

EMR-based Model of a Hybrid Braking for BEV

First results



Importance of non-average model

Conclusion and perspectives

Conclusion :

- Estimation of brakes temperature during a driving cycle
- Integration into a EMR-based model of a electric vehicle

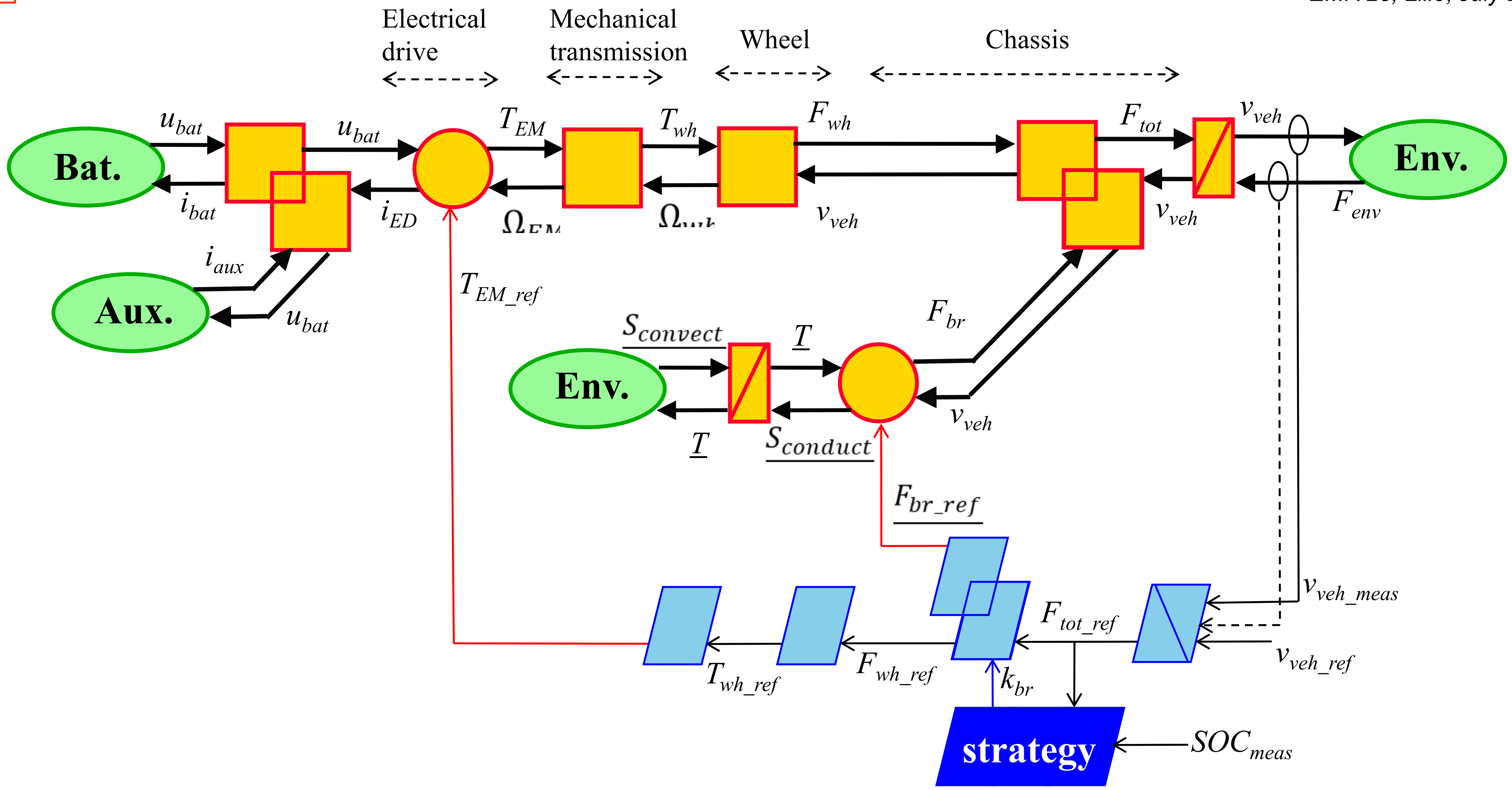
Perspectives :

- Creation of a map linking particles emissions and brake temperature
- Adaptive strategy to limitate particles emissions from braking

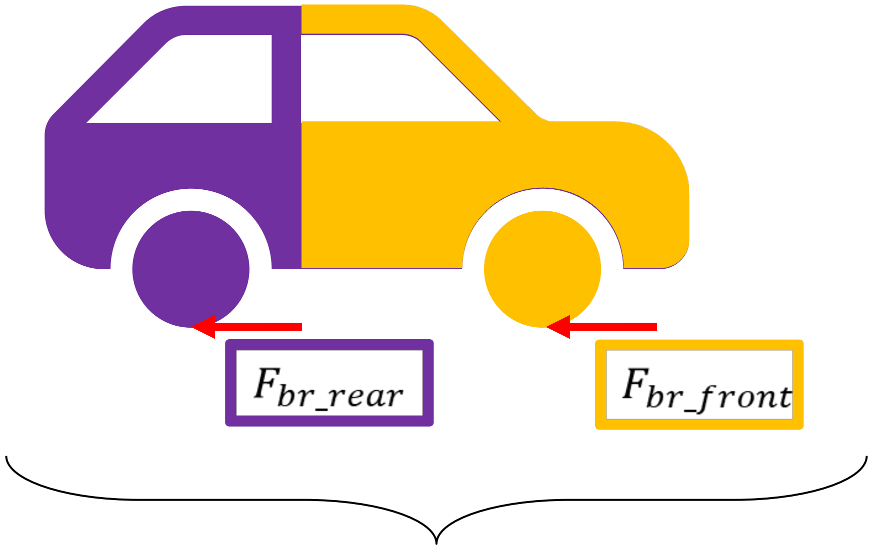
Thanks for your attention !

« Annex »

EMR representation



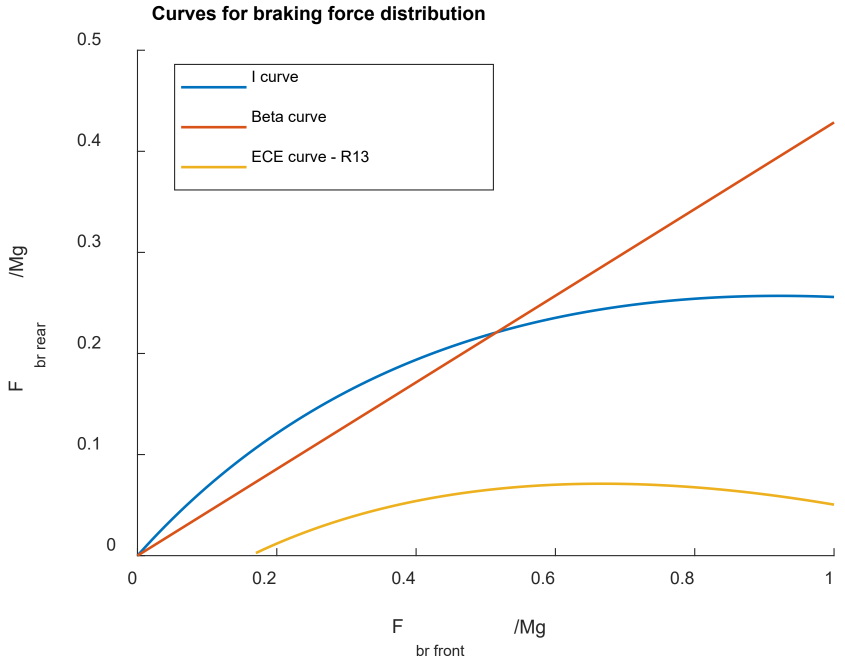
Braking repartition between front and rear brakes



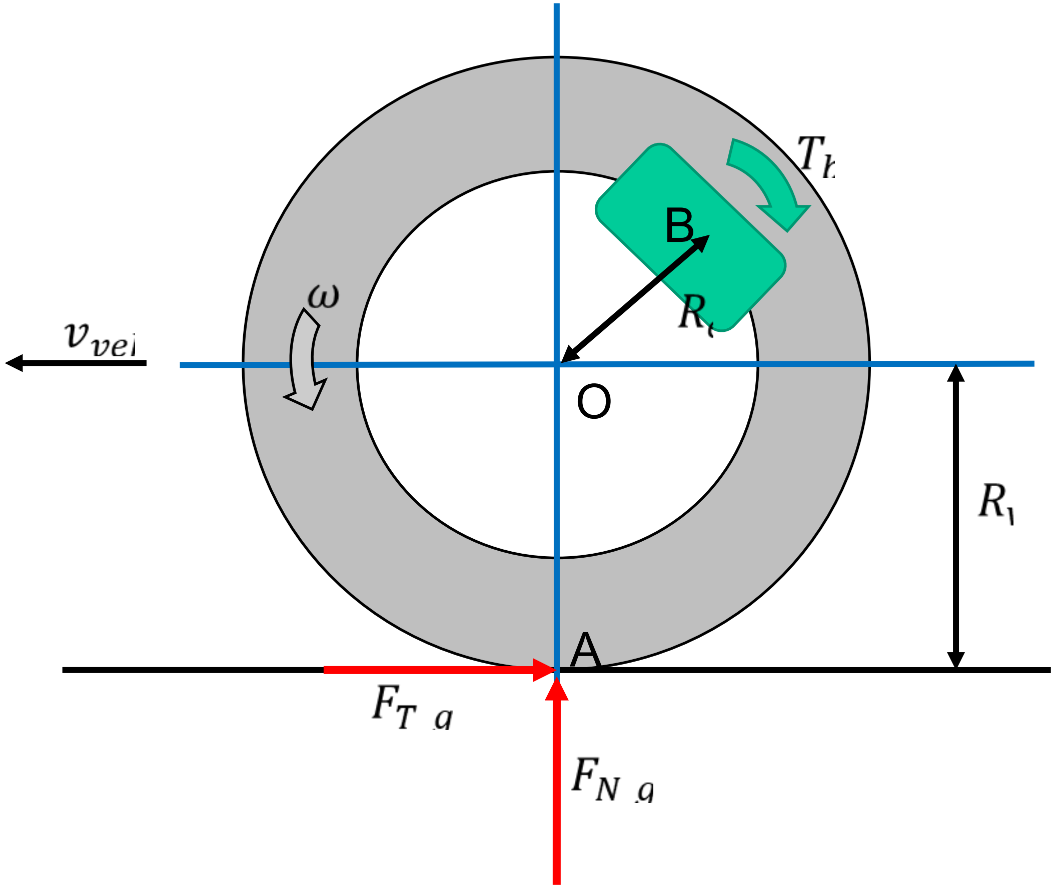
Industrial choice : fix distribution of braking between front and rear brakes : 70% at front and 30% at rear

Assumptions :

- Bicycle model : equidistribution of strength between left and right
- Only electrical braking available at front



Estimation of the heat flux



$$T_{br} = F_{T\_gr} R_{wh}$$
$$T_{br} = F_{T\_br} R_{eff\_br}$$

$$F_{T\_br} = \mu_{br} F_{N\_br}$$

$$\Phi_{th} = \mu_{br} F_{N\_br} v_{veh} \frac{R_{eff\_br}}{R_{wh}}$$

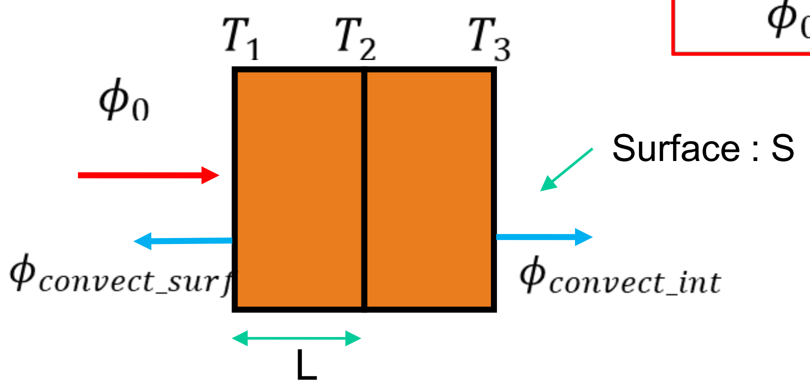
$$\Phi_{th} = \frac{R_{wh}}{R_{eff\_br}} F_{T\_gr} v_{veh} \frac{R_{eff\_br}}{R_{wh}}$$

$$\boxed{\Phi_{th} = F_{T\_gr} v_{veh}}$$

Thermal / electrical analogy for a simple example

Conduction effect

$$\phi_0 = F_{T\_gr} v_{veh}$$

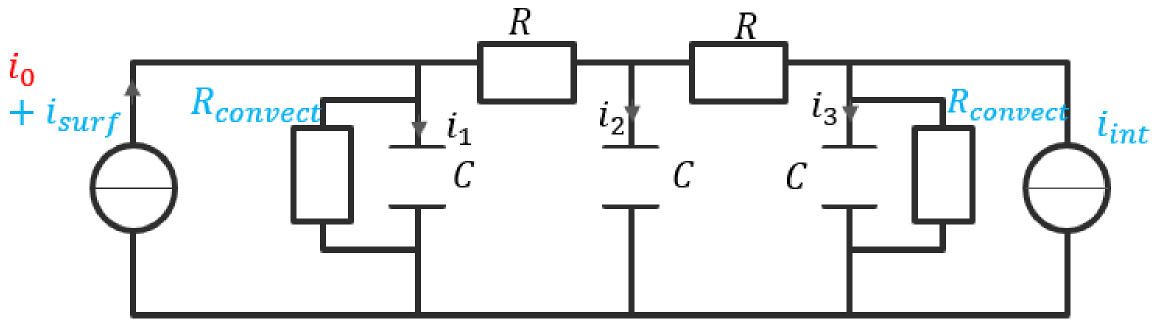


Convection effect

$$\phi_{convect\_surf} = h(\boldsymbol{v_{veh}})S(T_1 - T_{ext})$$

$$\phi_{convect\_int} = h(\boldsymbol{v_{veh}})S(T_3 - T_{ext})$$

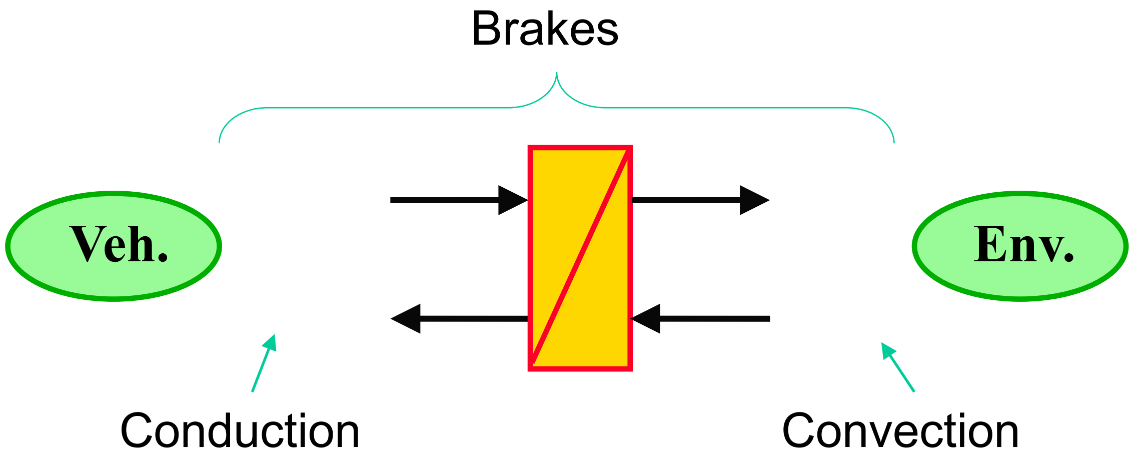
$$\begin{pmatrix} C_{th} & 0 & 0 \\ 0 & C_{th} & 0 \\ 0 & 0 & C_{th} \end{pmatrix} \begin{pmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \\ \frac{dT_3}{dt} \end{pmatrix} + \begin{pmatrix} \frac{1}{R_{th}} + hS & -\frac{1}{R_{th}} & 0 \\ -\frac{1}{R_{th}} & \frac{2}{R_{th}} & -\frac{1}{R_{th}} \\ 0 & -\frac{1}{R_{th}} & \frac{1}{R_{th}} + hS \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} \phi_0 + hST_{ext} \\ 0 \\ hST_{ext} \end{pmatrix}$$



$$\begin{pmatrix} C & 0 & 0 \\ 0 & C & 0 \\ 0 & 0 & C \end{pmatrix} \begin{pmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dot{u}_3 \end{pmatrix} + \begin{pmatrix} \frac{1}{R} + \frac{1}{R_{conv}} & -\frac{1}{R} & 0 \\ -\frac{1}{R} & \frac{2}{R} & -\frac{1}{R} \\ 0 & -\frac{1}{R} & \frac{1}{R} + \frac{1}{R_{conv}} \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix}$$

$$= \begin{pmatrix} i_0 + i_{surf} \\ 0 \\ i_{int} \end{pmatrix}$$

Implementation of the modelisation with EMR formalism



$\underline{\dot{q}}$ → in W

$\underline{T}$ → in K

Use of 2 entropy flow [W/K] :
$\underline{S_{conduct}}$ and $\underline{S_{convect}}$

« Biographies and references »

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