Energy from Regenerative Braking

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There are three possible approaches for calculating the energy lost/recovered due to regenerative braking:

1. The recovered energy finally available for later use

$$E_{regen,HV} = \sum_i \Delta t_i I_{HV,i} U_{HV,i} \tag{1}$$

   This definition does not account for the energy consumed by the electrical systems during braking. Therefore, it underestimates the recovered energy. However, when considering the Energy removed from the system (car), it does not accounts for the conversion losses.

2. Rotational energy at the MG's

$$\begin{aligned} E_{regen,MG} &= \sum_i \Delta t_i \left(M_{MG2,i}\omega_{MG2,i} + M_{MG1,i}\omega_{MG1,i} \right) \\ &= , \sum_i \Delta t_i \left(M_{MG2,i} RPM_{MG2,i} + M_{MG1,i} RPM_{MG1,i} \right) \frac{2\pi}{60} \end{aligned} \tag{2}$$

   where $M_{MG,i}$, $\omega_{MG,i}$ and $RPM_{MG,i}$ are the torques, the angular velocities and the revolutions per minute of the MG's, respectively. (Since I don't know if the energy from MG1 is exactly zero, I included it in the calculations.) This accounts for the energy consumption during braking but does not include the conversion losses between MG's and battery. This energy is larger than that available for later use.

3. Rotational energy removed from the system at the wheels by braking:

$$E_{regen,wheel} = \sum_i \Delta t_i 4 M_{brake,i} \omega_{wheel,i}, \tag{3}$$

   where $\omega_{wheel,i}$ is calculated from the velocity v (in ms^{-1}) of the car and the circumference $2\pi r$ of the wheel, i.e.

$$E_{regen,wheel} = \sum_i \Delta t_i 4 M_{brake,i} \frac{v_{car,i}}{2\pi r} 2\pi = \sum_i \Delta t_i 4 M_{brake,i} \frac{v_{car,i}}{r}. \tag{4}$$

   If the readings are correct, this should be the energy removed from the system. It should include all conversion losses.

Let's compare the three methods. This comparison will be not for the step i of the trip, but for the trips itself by summing up the individual contributions per trip as given in the equations above. The piece of code doing this is shown in figure 1. Here, $time = $\mathrm{\Delta t_i}$, $sp1 = $\mathrm{(trip\_dist_i - trip\_dist_{i-1})/\Delta t_i}$ is the speed of the car in km/h (therefore, the conversion factor of 1/3.6 to get the velocity in $\mathrm{ms^{-1}}$ is required) and 0.31045 is the radius of the wheel in metres. The energy is given in kWs.

In figure 2 the correlation is shown between the energies calculated per trip recovered/lost by regenerative braking. In figure 2a the energy generated by MG2+(MG1) generated by regenerative braking is compared to the energy stored in the battery. A very good correlation is observed. The

```
# rekuperierendes Bremsen

if ($brk_reg_trq != 0){
    $pRecupBrake1 += $time*($hv_a*$hv_v)/1000;
    $pRecupBrake  += ($mg2_torque*$mg2_rpm+$mg1_torque*$mg1_rpm)/60*2*$pi/1000*$time;
    $pRecupBrake2 += $brk_reg_trq*$sp1/3.6/0.31045*4*$time/1000;
}
```

Figure 1: Code snippet for calculating the different energies playing a rôle during regenerative braking.

fact that the correlation is above the red line, for which both energies would be equal, indicates that the current loaded to the battery is lower by the amount needed to support the electrical systems plus conversion losses for this stage. In figure 2b the energy recovered at the wheels by the regenerative braking is compared with the energy produced by MG2+(MG1). Also in this case a very good correlation is visible, which is not as narrow as in case of figure 2a. Also here the distribution of measurements lies above the line of equality, which is most probable due to transmission losses.

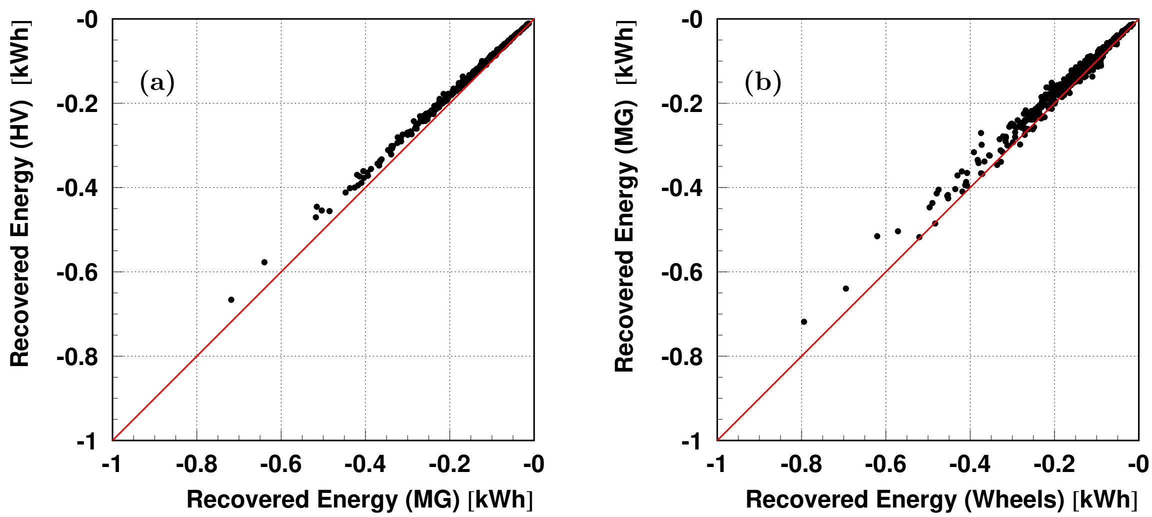

Figure 2: Correlation of recovered energy: (a) energy going to the Battery vs. rotational energy from MG and (b) of the rotational energies from MG vs. wheels. Equality of the quantities is indicated by the red line.

In figure 3 the ratios of $E_{regen,HV}/E_{regen,MG}$, $E_{regen,MG}/E_{regen,wheel}$ and $E_{regen,HV}/E_{regen,wheel}$ are shown. For $E_{regen,HV}/E_{regen,MG}$ a very narrow distribution is visible with a mean value of 0.91 with a resolution of 0.016. You have to keep in mind, that the current drawn from the battery for the electrical system is included in this ratio. No attempt is made, to apply a correction due to this. The resolution of the distribution of $E_{regen,MG}/E_{regen,wheel}$ is worse, with still is a quite good value of 0.07. The mean value is 0.90. Finally, the ratio $E_{regen,HV}/E_{regen,wheel}$ is also shown. The resolution is the same as for $E_{regen,MG}/E_{regen,wheel}$, as expected in case of uncorrelated uncertainties and the mean value of 0.81 for the complete chain is the consistent with the product of the two other ratios.

When considering the HV energy it has to be taken into account that the current going to the battery is lower than the current generated by MG2 by the current needed for the electrical systems, i.e.

$$I_{battery} = I_{MG2} - I_{consumers} \tag{5}$$

and correspondingly for the energies (ordered slightly differently):

$$E_{regen,MG} = E_{regen,HV} + E_{consumers}. \tag{6}$$

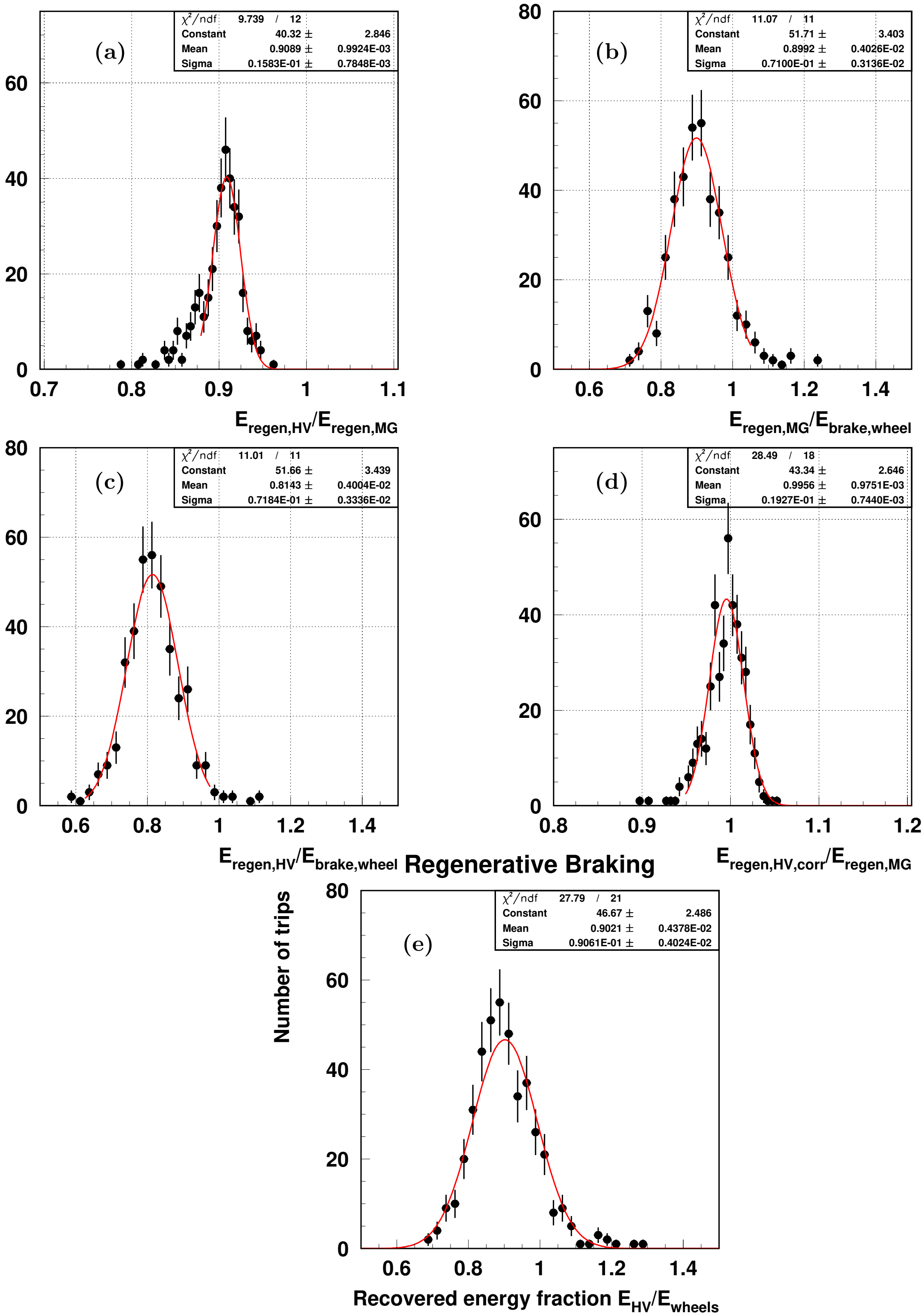

Figure 3: Ratio (a) $E_{regen,HV}/E_{regen,MG}$, (b) $E_{regen,MG}/E_{regen,wheel}$, (c) $E_{regen,HV}/E_{regen,wheel}$, (d) $E_{regen,HV,corr}/E_{regen,MG}$ and $E_{regen,HV,corr}/E_{regen,wheel}$. The red lines are the results of fits to the data using a Gaussian.

When accounting for the average energy $\langle E_{consumers} \rangle$ needed to sustain the electrical systems, the transfer efficiency from the wheels to the battery is about 90 %, as can be seen in figure 3e.