The possibility for energy regeneration by electrification in Swedish car driving

EVS27
Barcelona, Spain, November 17-20, 2013

The possibility for energy regeneration by electrification in Swedish car driving

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Abstract

The ability to regenerate energy when braking is a valuable advantage of hybrid and fully electric vehicles. How much energy that can be regenerated depends mainly on the car driving and the capacity of the driveline. Detailed studies of possibilities for brake energy regeneration in real world driving are needed to better understand the potential gains of car-electrification since test cycles do not take individual driving or elevation into account. This study has analysed the potential for regeneration in Swedish car driving by applying a model for a normalized vehicle to a highly detailed and representative data set of individual car movements for privately driven cars in Sweden.

The share of energy at the wheels used for braking was found to range from 12% to 63%, with an average of 30%. Engine braking could however reduce the amount of recoverable energy to about 16%. On average 42% and 89% of the potentially regenerable energy is available below 10 and 40 kW, respectively. Drivers with lower average speed have in general a higher share of the energy at the wheels potentially available for regeneration. This is however not an important factor to determine the total yearly energy/cost savings. Instead the yearly mileage is shown to be a more relevant indicator on total energy savings from regeneration. The results are compared to the NEDC and WLTP test cycles.

Keywords: Regenerative braking, GPS, Sweden, Electrification

1 Introduction

Electrification of vehicle drivelines stretches from simple stop/start systems, over different variants of HEV and PHEV, to fully electric vehicles. A common feature for most of them is the ability to regenerate energy when braking. How much recovered energy that can be expected is interesting both from an environmental point of view and in terms of user economics. The share of energy available for regeneration actually harvested depends mainly on the (regenerative) capacity of the driveline, stability and safety requirements in operation, and the actual driving.

Benefits from hybridisation in terms of energy from regeneration has been analysed on test cycles [1]. However standardised test cycles, as the NEDC, used for emission certification and fuel use labelling, are often not very representative for real world driving [2]. Also they do not in general include altitude profiles of the driving. Further it is often claimed that city driving, with a low average speed and a lot of starts and stops, is one of the types of driving that have most to gain from regeneration, rather than highway driving or driving in the countryside. Martins et al. use a powertrain model of a PHEV to analyse available energy from regenerative braking for different driving cycles, showing braking energy can represent up to 70% of useful motor energy for some urban driving conditions and about 40% and 18% for suburban and motorway conditions, respectively [3]. Most car owners are however not solely city drivers or highway drivers, making analysis based on real world driving of high interest.

The aim of this study has been to analyse the possibilities for regeneration in Swedish driving by utilizing a highly detailed and representative data set of individual car movements.

2 Method

To estimate the potential of energy regeneration by electrification of Swedish car driving we utilise speed and altitude data from real world driving of Swedish cars. These individual car movement data are used together with a model for the power and energy fluxes at the wheels for a normalized car. The speed profiles of the NEDC and WLTP test cycles are also used for comparison.

2.1 The vehicle model

The power *P(t)* at the wheels needed to produce the desired movement in terms of speed *v(t)* and road gradient $\alpha(t)$ in the car model is given by:

$$P(t) = P_{acc}(t) + P_{air}(t) + P_{roll}(t) + P_{grade}(t) \quad (1)$$

$$P_{acc}(t) = m * a(t) * v(t) \quad (2)$$

$$P_{air}(t) = \frac{1}{2}\rho_a * A * C_d * v^3(t) \quad (3)$$

$$P_{roll}(t) = c_r * m * g * \cos(\alpha(t)) * v(t) \quad (4)$$

$$P_{grade}(t) = m * g * sin(\alpha(t)) * v(t) \quad (5)$$

Here P_{acc} is the power needed/gained to accelerate/decelerate the vehicle. P_{air} and P_{roll} are the power required to overcome air drag and rolling resistance respectively and P_{grade} the power required/gained in case of a road gradient. The term m is the mass of the vehicle, $a(t)$ is the acceleration at time t, ρ_a is the density of the surrounding air, A is the frontal area of the car, C_d is the air drag coefficient, c_r is the rolling friction coefficient and g is the acceleration due to gravity.

The power demand can be divided into dissipative power demands, where the energy is transformed into unrecoverable heat (P_{air}, P_{roll}), and conservative power demands where the energy is transformed into a potentially recoverable form of energy, i.e. kinetic energy ($P_{acc,}$) and potential energy (P_{grade}) [1]. When decelerating or driving downhill P_{acc} and P_{grade}, respectively, turn negative, and can substitute traction power to, for example, overcome the power demand for air drag or rolling resistance. Any excess negative power will, in a conventional vehicle, be transformed to heat by braking. It is this excess negative power that potentially can be utilised for regeneration in a hybrid or electric driveline. The total energy supplied to the wheels is found as the integral over positive *P(t)*, that is when the car is in traction mode:

$$E_{trac} = \int P(t)dt\,,\ when\ \mathrm{P(t)} > 0 \quad (6)$$

The total amount of energy that potentially can be regenerated, E_{regpot}, is what is braked away, which is identified by:

$$E_{regpot} = E_{brake} = \int P(t)dt\,,\ when\ P(t) < 0 \quad (7)$$

Since P_{acc} and P_{grade} are “costing” energy only when the associated stored energy is dissipated in braking the total energy supplied for the vehicle is also:

$$E_{trac} = E_{air} + E_{roll} + E_{brake} \quad (8)$$

The total share of supplied energy at the wheels that potentially can be regenerated is thus:

$$\frac{E_{regpot}}{E_{trac}} \quad (9)$$

In a hybrid electric vehicle with direct mechanical connection between the engine and the wheels, a substantial part of the braking energy E_{brake} can be expected to be dissipated through engine braking, $E_{enginebrake}$. The available energy may therefore be $E_{footbrake} = E_{brake} - E_{enginebrake}$ for a hybrid electric car. In a fully electric car all braking energy could potentially be regenerated. However several other factors such as stability and safety requirements in operation and the driveline design may further restrict the amount of regenerable energy. The recoverable energy E_{rec} is defined as the energy available after deducting engine braking and power limitations. Depending on the conversion efficiency within the vehicle a certain amount E_{reused} of the regenerated energy can then be part of the wheel energy supply E_{trac}.

We assume the car to be a normalised midsize car with mass m = 1500 kg and air resistance C_d*A = 0.70 m^2, which are close to the values (1490 kg and 0.706 m^2, respectively) for the average vehicle

sold in Sweden 2007 [4][1]. The rolling resistance has been assumed to c_r = 0.01 which is reasonable for a passenger car [5].
We approximate the force in engine braking with the idling friction of 0.160 kW/rps from a 2-liter gasoline engine [6]. The engine speed is assumed to be on average 1761 rpm, the estimated average engine speed for a 6-gear car when engine braking on the NEDC test cycle. This results in an average power of engine braking of 4.7 kW.

2.2 Individual car movements

We use a recently available car movement data set containing GPS loggings of individual movement patterns for about 430 privately driven Swedish cars each followed for between 1 and 2 months during 2010-2012 [7], [8]. The measurement is performed on relatively new cars, 9 years old or newer and the total driving comprises around 1 137 500 km. The participants were recruited by mail from a randomly drawn selection of an excerpt of car owners from the Swedish vehicle register and the measurements are from all seasons of the year. The loggings were done with a frequency of 2.5 Hz, which gives good prerequisites to investigate the power and energy fluxes at the wheels in driving. The speed and altitude were measured directly by the GPS-equipment while the acceleration at point of time t has been derived from the measured speed at t +/-1.
Retardation can be conducted without any braking by sole influence of the air drag and rolling resistance. Since these resistances are vehicle specific we cannot always, by using a normalized car, determine for the individual car, if it actually was braking or not in a specific point in time in the driving pattern. A car with less (better) aerodynamic properties would compared to the normalized vehicle in reality have less (more) energy available for regeneration than our modelling suggests. Also the individual mass of the vehicle will influence the possible regeneration. The masses of the vehicles themselves vary, as do the loads in the form of passengers and luggage. Also any towed load will influence the mass as well as the aerodynamic resistance.

[1] The mass for sold cars is the curb weight, which includes a driver and necessary fluids.

3 Results

3.1 Recovery potential

Figure 1 depicts the average energy lost per 10 km of driving due to rolling resistance, air drag and braking respectively. Specific braking energy varies by a factor four between individual movement patterns and ranges from around 0.2 to 0.9 kWh/10 km. The share of energy at the wheel lost through braking varies between 12% and 63%, Fig. 2a.

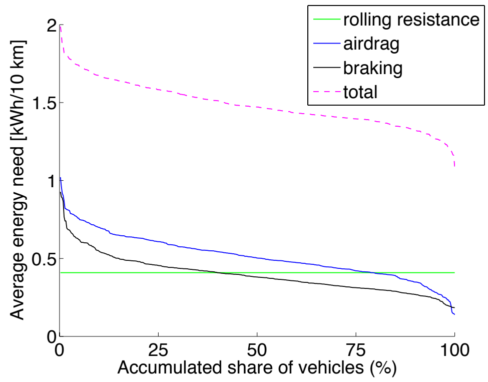

Figure 1: For the assumed car, for each movement pattern, the average losses of energy at the wheels. For comparison of movement patterns, the energy losses are for all patterns normalized to the losses of an assumed midsize car (mass m = 1500 kg, air resistance $C_d *A$ = 0.70 m^2, and rolling resistance c_r = 0.01). Note: Each curve is sorted independently.

The average share of braking energy losses, for the here used movement patterns, is 30%. This is close to the share of 29% and 27% for the normalized car following the NEDC and the suggested WLTP [9] test cycles respectively, Fig 2b. Even though test cycles are designed by using data from real world driving they will unavoidably introduce flaws into the regeneration analysis by neglecting elevation. For the movement patterns used here, when neglecting the altitude profile the average share of braking energy decreases to about 26%.
Earlier studies have shown higher regeneration gains for cars driving with lower average velocity. This can be noted in Fig. 2b, where test subcycles with lower (higher) average speed gives a higher (lower) share of braking energy. The results from the individual movement patterns also suggest that driving in lower speeds tends to give a higher share of braking energy, Fig. 3a. On the other hand there is no clear correlation between share of braking energy at the wheels and total yearly braking energy, Fig. 3b. What instead seems to be important for the total yearly braking energy is the yearly distance Fig. 3c. This even though the

yearly driven distance correlates poorly with the share of energy lost due to braking.
The share of energy available for regeneration actually harvested depends on the power limitations of the electric components in the driveline. Figure 4a and b give the power levels of braking and the share of cumulative braking energy lost up to a given power level, respectively. This gives an indication of the power requirements of regeneration equipment; 10 kW will on average cover 42% of the available braking energy (E_{regpot}) for the driving patterns, while 40 kW will on average cover 89%. The solid black and the dashed black lines depict the average for the 10% of fleet with lowest and highest average velocity, respectively. The cars driving faster generally have a larger share of the braking occurring at higher power levels compared to the slower driving cars.
The investigated test cycles include a low share of braking energy above 20 kW and no braking energy over 30 kW. The cumulative share of total regeneration for the NEDC lies close to or above the slowest 10% of the vehicles in the data set, Fig 4b. The same goes for WLTP for power levels above 15 kW. The regenerative performance of electric drivelines might thus be overvalued in testing on these cycles compared to average real world driving in Sweden. Also both test cycles include relatively few working points, which make it possible for car manufacturers to optimise their driveline on the specific test cycle.

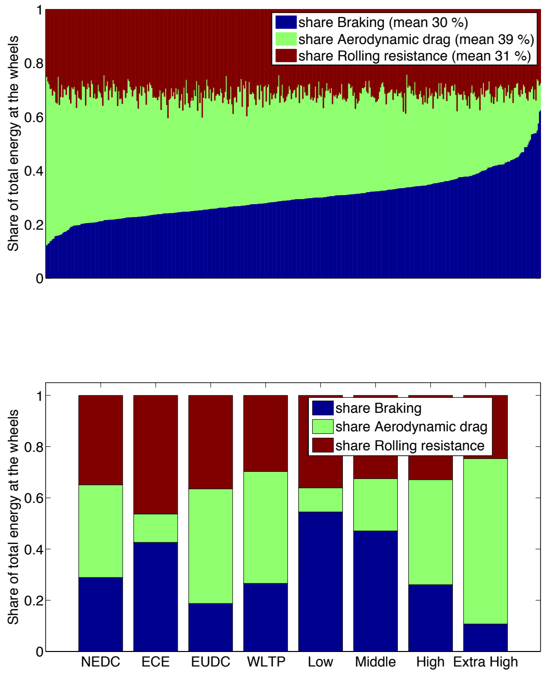

Figure 2. a) For the assumed car, for each movement pattern, the shares of energy lost at the wheels through braking, air drag and rolling resistance, respectively. Sorted after share of energy lost through braking. b) The corresponding shares when the car follows the NEDC, ECE, EUDC, WLTP, WLTP low, WLTP middle, WLTP high and WLTP extra high test cycle, respectively.

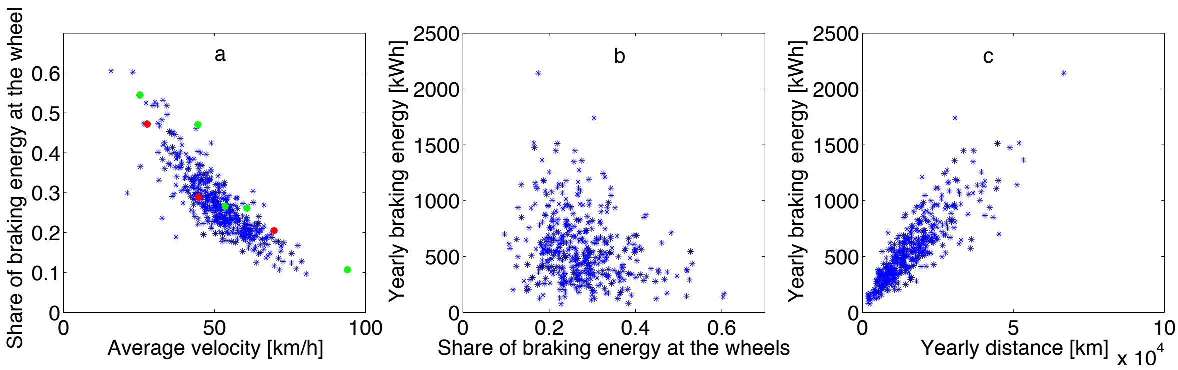

Figure 3. For the assumed car, for each movement pattern, a) the share of energy (at the wheels) lost trough braking as a function of average velocity, red dots represents the values for NEDC, ECE and EUDC and green dots represents WLTP, low, middle, high, extra high; b) the total energy lost yearly (at the wheels) through braking as a function of the share of energy (at the wheels) lost through braking; c) total energy lost yearly (at the wheels) through braking as a function of the yearly mileage.

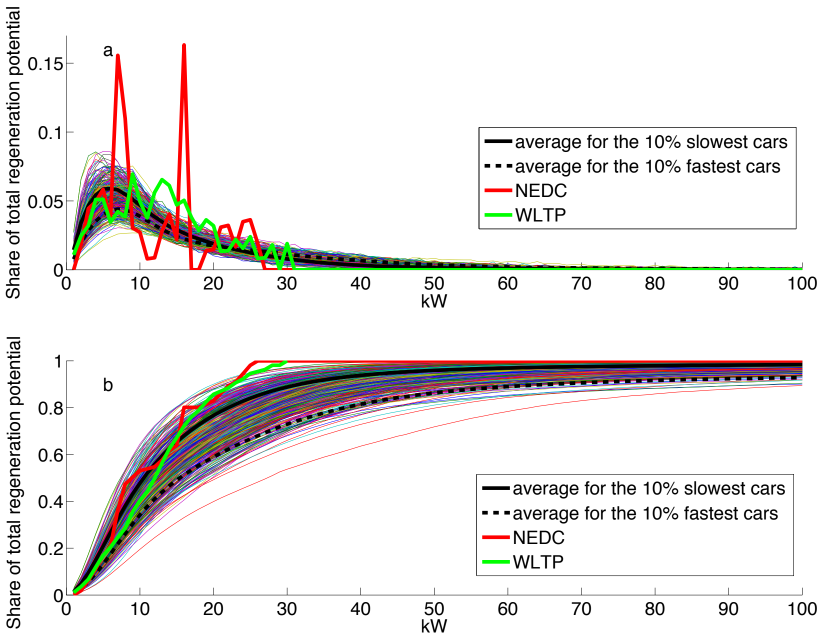

Figure 4. For the assumed car, for each movement pattern as function of power level a) the share, and b) the cumulative share, respectively, of the regeneration potential.

3.2 Practical energy recovery and savings

How large share of the braking energy that can be recovered depends on the design of the driveline. To illustrate this we investigate two simple exemplary drivelines, one "battery electric vehicle" (BEV) and one "mild hybrid" (mHEV), each limited only by their maximum power and efficiency in regeneration. The assumptions, average regeneration potential and savings for respective driveline are described in Table 1.

For the BEV the average share of potentially recoverable energy (E_{rec}/E_{trac}) is close to the case with no power limitations, showing that there is not much regenerative energy to gain from an increase in maximum regeneration power above 40 kW.

For (mild) hybrids the ultimate potential recovery can be limited to the share of foot braking energy, which for the assumed car is on average 16%, Fig. 5. The regeneration power limit constrains the potential energy recovery for the mHEV (Fig. 6) to about one fifth of the BEV's. The power distribution of the potential regeneration for a car with engine braking should reasonably be similar to what is depicted in Fig. 4 but shifted towards lower power levels. An average of 35% of the recoverable energy (E_{rec}) can be reached with a mild hybrid, compared to 42% in the case of no engine braking depicted in Fig. 4.

An electrification of the drivetrain enables cost savings from energy regeneration, but it often means an increased cost for the car at purchase. It is therefore interesting not only to look at the share of energy consumption that corresponds to braking but also how much energy that is lost annually through braking.

Table 1: Assumptions, average regeneration potential and savings for the two examplary drivelines

	BEV	mHEV
Power limit	40 kW[a]	10 kW[b]
Engine braking	-	4.7 kW
Two-way efficiency[d]	0.6[c]	0.5
Driveline efficiency	0.72[c]	0.17[c]
Charger efficiency	0.94[c]	-
Share regen. potential, E_{regpot}/E_{trac}	30%	
Share recoverable energy, E_{rec}/E_{trac}	27%	5.5%
Share reusable energy, E_{reused}/E_{trac}	16%	2.8%
Yearly savings at the wheels, E_{reused}	510 kWh	51 kWh
Yearly savings at electric outlet/tank, $E_{reused}/\eta_{driveline}$	750 kWh	300 kWh

Notes: a) approximately the same as the Nissan Leaf, b) In mHEV braking also occurs with the engine hcnce regeneration occurs first after the engine has withdrawn an assumed 4.7 kW of engine braking power, c) see Guzzella et al. [5], d) the combined efficiency in charging the battery and later decharging for use.

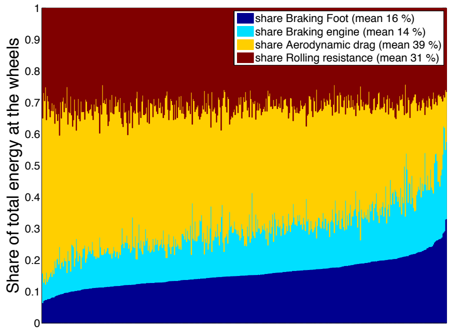

Figure 5. For the assumed car, for each movement pattern, the shares of the traction energy lost through foot braking, engine braking, air drag and rolling resistance, respectively, sorted after energy lost through foot braking.

By scaling the measured driving periods to a full year of driving, the saving ($E_{resused}$) would on average be ten times higher at the wheels for the BEV, Fig. 7, compared to the mHEV.

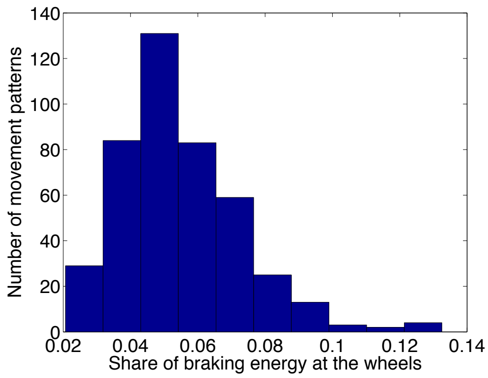

Figure 6: For the assumed mHEV, distribution of the share of recoverable energy, E_{rec}/E_{trac}, for individual movement patterns

However the total energy saved is for a BEV at the electric outlet on average only a bit more than twice as high as the yearly savings from the assumed mHEV at the tank. The average yearly saved energy in the mHEV corresponds to about 31 litres of gasoline varying from about 4 to around 111 litres per year. At current Swedish gasoline price of around 1.6€ per litre and assuming an annuity of 0.15 (corresponding to for instance an annuity loan over 8 years with an interest rate of 5%), the average fuel savings can balance an extra investment of about 330 € for the regeneration technology.

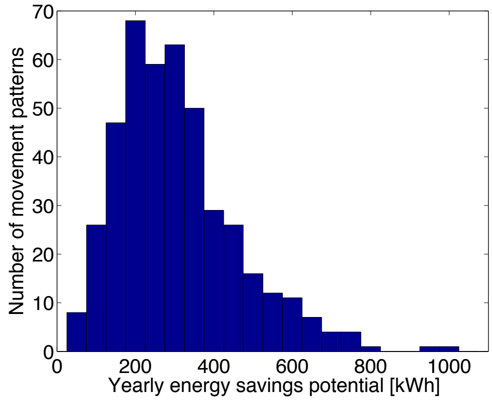

Figure 7. For the assumed BEV, the estimated annually reused energy from regenerative braking, E_{reused}.

4 Discussion

Which drivers do actually benefit most from regenerative braking? This is interesting both from an environmental point of view and as part of the driver economics. Earlier studies have shown higher share of energy recovery for cars driving with low average velocity and many starts and stops. Our result confirms these results but also points out that low velocity is not the major parameter determining the yearly energy savings, Instead the yearly mileage is shown to be a more important indicator. The drivers with a high yearly mileage could therefore be targeted as potential early adopters of regenerative technologies.

Discrepancies in braking power profile between the test cycles and real car movement patterns can be increasingly problematic, when striving towards lower fuel consumption and CO_2 emissions. Car models could be optimised for good results on test cycles while the performance in real world driving might be limited. Future research would also benefit from a more detailed assessment on how the possibilities for regeneration depend on the amount of hilly driving.

Conclusions

The use of data from real world driving (including altitude data) is important for better understanding and estimates of the potential benefits from regeneration technology.

Acknowledgments

This analysis was done with support from the Chalmers Energy Initiative, which is greatly acknowledged.

References

[1] Ott, T., Zurbriggen, F., Onder, C., Guzzella, L.: *Cycle Averaged Efficiency of Hybrid Electric Vehicles*. Accepted for Publication in the Journal of Automobile Engineering (2012) *Vehicle Propulsion Systems, Introduction to Modeling and Optimization,* third edition, Springer, Berlin Heidelberg, 2013.

[2] Mock, P., German, J., Bandivadekar, A., Riemersma, I.: Discrepancies between type-approval and "real-world fuel-consumption and CO2 values. The International Council on Clean Transportation (2012).

[3] L. Martins et al., *Regenerative braking potential and energy simulations for a plug-in hybrid electric vehicle under real driving conditions,* Proceedings of IMECE09: 2009 ASME International Mechanical Engineering Congress and Exposition November 13-19, 2009, Lake Buena Vista, Florida, USA.

[4] F Sprei, S Karlsson, *Shifting Fuels, Downsizing or Both? – The Swedish Example.* Transportation Res Part D 18(2013), 62-69.

[5] L. Guzzella, A. Sciarretta, *Vehicle Propulsion Systems, Introduction to Modeling and Optimization,* third edition, Springer Berlin Heidelberg, 2013.

[6] M. Ross, *Fuel efficiency and the physics of automobiles*, Contemporary Physics 38(1997), 381-394.

[7] S. Karlsson, L.-H. Kullingsjö, *The Swedish car movement data project*, Dep. of Energy and Environment, Chalmers Univ of Technology, Gothenburg, Sweden, 2013.

[8] S. Karlsson, L.-H. Kullingsjö, *GPS measurement of Swedish car movements for assessment of possible electrification,* Proceedings of EVS27, Nov 17-20, Spain, 2013.

[9] M. Tutuianu et al., Development of a World-wide harmonized Light duty driving Test Cycle, Draft Technical Report, DHC subgroup, 2013.

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