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The potential for brake energy regeneration under Swedish conditions

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HIGHLIGHTS

- Potential regenerative braking is analyzed by using Swedish GPS-measured drive cycles.
- Results from the measured drive cycles are compared to the NEDC and WLTP test cycles.
- Regeneration potential varies by a factor of six among individual movement patterns.
- City drivers have highest potential to regenerate energy per km of driving.
- Long distance drivers have highest potential to regenerate energy on a yearly basis.

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ABSTRACT

The ability to regenerate energy when braking is a valuable advantage of hybrid and fully electric vehicles. The regeneration potential mainly depends on how a car is driven and on the capacity of the drivetrain. Detailed studies of the regeneration potential based on brake energy in real-world driving are needed to better understand the potential gains of car-electrification, since test cycles do not take individual driving characteristics or route elevation into account. This study uses a model of a normalized vehicle and a highly detailed and representative data set of individual car movements including elevation to analyze the potential for energy regeneration in cars when driven under current real-world Swedish conditions.

The ultimate energy regeneration potential (defined as the braking energy at the wheels) varies by about a factor of six among individual movement patterns, with an average of 0.033 kW h/km, corresponding to 27% of the total average energy supplied at the wheels. Earlier studies have shown a higher energy regeneration potential per km for cars driving under urban conditions with low average velocity and many starts and stops. Our results confirm this but also point out that a low average velocity and a high share of city driving are not very well correlated with the yearly energy savings; for this the yearly mileage is a more important indicator. This suggests that drivers who rack up the miles should be targeted as potential early adopters of regenerative technologies rather than city drivers per se. The results from real-world driving are compared to the NEDC and WLTP test cycles.

1. Introduction

Electrification of vehicle drivetrains ranges from simple stop/start systems, across different variants of hybrid and plug-in hybrid electric vehicles (HEVs and PHEVs), to fully electric vehicles. A common feature for all but the simplest systems is the ability to regenerate energy when braking. Earlier studies analyzing the potential benefits from hybridization and electrification have often only indirectly analyzed the gains from brake energy regeneration. The amount of energy that can be regenerated is however of interest to understand the regeneration technology's viability and possibilities to reduce greenhouse gas emissions, local pollutants, energy insecurity and driver's running costs. For so called mild hybrids (mHEVs) brake energy regeneration is one of the most valuable benefits compared to a conventional car and to understand the potential for brake energy regeneration is therefore of key importance to properly evaluate the possible gains from a large scale introduction of mHEVs. The regeneration potential in a given car depends mainly on how the car is driven and on the regeneration power capacity of the drivetrain. Earlier studies have shown that increasing the power capacity leads to a higher amount of braking energy being available for regeneration but with diminishing returns [1,2]. In addition, the returns per installed power

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capacity, per trip and on yearly basis, will depend on the usage pattern of the individual car and should thus be considered also in the dimensioning of the power capacity.

When it comes to analysis of cars' usage patterns estimates of the potential benefits of regenerative braking have been conducted for vehicles based on standardized driving test cycles (see for example [1–9]). These studies have pointed to city driving, with low average speed and many starts and stops as having the largest potential for gains from regeneration [3,4,6,7]. Martins et al. used a powertrain model of a PHEV to analyze available energy from regenerative braking for different driving cycles and showed that 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 [6]. However, most car users are not exclusively city drivers or highway drivers, so analyses based on real-world driving are of great interest. Regional differences have to some extent been discussed by comparing American test cycles with test cycles from China and India [2,8] and by comparing European, American and Japanese drive cycles [5]. In the study of Sovran et al. the European and American cycles gave very similar results while the Japanese drive cycle resulted in a greater percentage benefit from regenerative braking, primarily because of lower average speed and thus lower losses to aerodynamic drag [5].

The test cycles' ability to represent real world driving has been questioned. For example the new European drive cycle (NEDC), used for emission certification and fuel use labelling in Europe, is not very representative of real-world driving [10,11], and does not, for instance, include the vertical driving profile, although a number of studies have shown the importance of road grade for fuel consumption and emissions [12–14]. To reach a harmonized approach for CO_2- and pollutants-testing for passenger cars for all regions, the UN Economic Commission for Europe initiated a project to develop new testing procedures, the Worldwide harmonized Light vehicles Test Procedure (WLTP) [15,16]. The WLTP drive cycle will include more realistic accelerations and more dynamic speed variations to reach more accurate fuel and emission estimates [10]. Although improved, the drive cycle still includes somewhat low levels of accelerations compared to how many drivers actually drive, since the cycle has to be drivable in all cars [10] and data on road gradient are still not included. Data on road grade is important also in the analysis of hybrid and electric vehicles [17,18]. Another problem with standardized test cycles is that the diversity in between individual drivers in the car fleet is missed, which would be of importance for example when analyzing which drivers could be expected to reach highest benefits from hybridization. Estimates of the potential benefits of regenerative braking have also been derived from drive cycles collected from real-world driving. However, there is a general lack of good and representative data sets. The datasets that have been used are often not representative of any larger group of drivers. The drive cycles have for instance been collected from one or a small number of predefined routes, see for example [18,19].

In Sweden individual multiday drive cycles given by speed and altitude have been logged by GPS for a number of privately driven conventional cars aiming at obtaining a representative sample of Swedish driving [20,21]. This data set gives us a unique opportunity to analyze the potential energy savings from brake energy regeneration. The main aim of this study is to analyze the regeneration potential for Swedish driving conditions by utilizing this comprehensive dataset of individual car movements. The results for these drive cycles are compared to the corresponding results for the NEDC and WLTP test cycles. We will further do a rough estimate of what levels of energy savings that can be achievable in practice by investigating two drivetrains, a "battery electric vehicle" (BEV) and a "mild hybrid" (mHEV).

2. Method

To estimate the overall potential for energy regeneration under Swedish car-driving conditions, we utilize GPS-derived speed and altitude data from real-world car-driving in Sweden. 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 used for comparison. How large share of the regeneration potential that can be utilized will depend on the specific drivetrain design. To better illustrate this we therefore perform a rough estimate of how power limitations of the electric drivetrain and engine braking (in case of a HEV) may limit the amount of energy available for regeneration.

2.1. The vehicle model

The power-at-the-wheels $P(t)$ needed to produce the desired movement in terms of speed $v(t)$ and road gradient $\alpha(t)$ is given by[1]:

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

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

$$P_{grade}(t) = m * g * \sin(\alpha(t)) * v(t) \tag{3}$$

$$P_{air}(t) = \frac{1}{2}\rho_a * A * C_d * v^3(t) \tag{4}$$

$$P_{roll}(t) = c_r * m * g * v(t) \tag{5}$$

Here, P_{acc} is the power needed/gained to accelerate/decelerate the vehicle, and P_{grade} the power required/gained in case of a road gradient. P_{air} and P_{roll} are the powers required to overcome air drag and rolling resistance, respectively. Further, 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 (driving downhill), P_{acc} (P_{grade}), turns negative and can substitute for traction power to overcome, for example, the power demand for air drag or rolling resistance. In a conventional vehicle any excess negative power will, be transformed to heat through braking. This excess negative power can potentially be utilized for regeneration. We thus have:

$$P_{trac} = P(t), \text{ when } P(t) > 0 \tag{6}$$

$$P_{brake} = -P(t), \text{ when } P(t) < 0 \tag{7}$$

The total energy supplied to the wheels is found as the integral over positive P or $P_{trac}(t)$, that is when the car is in traction mode:

$$E_{trac} = \int P_{trac}(t)dt \tag{8}$$

The maximum amount of energy that potentially can be regenerated is the energy that in a conventional vehicle would be lost through braking, which is found as:

$$E_{brake} = \int P_{brake}(t)dt \tag{9}$$

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[1] Neglecting other disturbances such as tires slipping, headwind, and friction due to cornering.

Since P_{acc} and P_{grade} only “cost” energy when the associated stored energy is dissipated by braking, the total energy supplied to the vehicle is also:

$$E_{trac} = E_{air} + E_{roll} + E_{brake} \tag{10}$$

We define the potential for brake energy regeneration as:

$$E_{potregen} \equiv E_{brake} = E_{trac} - (E_{air} + E_{roll}) \tag{11}$$

For convenience and clarity, we henceforth denote the regeneration potential as E_{brake}. The possible regeneration will depend on the vehicle and other parameters besides the drivetrain. Vehicle retardation can be conducted without any braking, solely by air drag and rolling resistance. Since these resistances are vehicle-, load-, road- and weather-specific, we cannot unambiguously determine for an actual individual car with data logged if it actually was braking or not at a specific point in time in the drive cycle by modelling the energy fluxes for a normalized car. Rolling resistance depends on tire type and wear, pressure, road type, etc. A car with worse (better) aerodynamic properties would have less (more) energy available for regeneration than our modelling suggests. The mass of the vehicle influences the possible regeneration, also, as does the load, in the form of passengers and luggage. Any towed load will influence mass as well as aerodynamic and rolling resistance. Driving in windy conditions results in changed aerodynamic resistance.

In our base case, we estimate the regeneration potential for a normalized midsize car with mass $m = 1500$ kg and air resistance $C_d \cdot A = 0.70\ \text{m}^2$; these are close to the values for the average vehicle sold in Sweden in 2007 (1490 kg and 0.706 m^2, respectively) [22].[2] The rolling resistance coefficient is assumed to be $c_r = 0.01$, which is reasonable for a passenger car [23].

2.2. Drivetrain design

In a hybrid electric vehicle with a direct mechanical connection between the engine and the wheels, a substantial part of the braking power P_{brake} may be dissipated through engine-braking, $P_{enginebrake}$. Also the power limitations of the electric drivetrain will restrain the amount of braking energy available for regeneration. The *recoverable* energy E_{recov} is here defined as

$$E_{recov} \equiv \int (P_{brake}(t) - P_{enginebrake}(t))dt,$$
$$\text{where } (P_{brake}(t) - P_{enginebrake}(t)) < \text{power limitation} \tag{12}$$

Several other factors, such as stability and safety requirements in operation and the drivetrain design, may further restrict the amount of regenerable energy and E_{recov} should thus be considered as an upper potential.

The conversion efficiency from wheel to battery and back to wheel, η_{regen}, will vary with a number of factors such as drivetrain design, braking power and present battery state of charge. As a first order approximation we assume η_{regen} to be constant over a drive cycle, only varied between BEV and mHEV. The amount of reusable energy E_{reuse} that can be part of the wheel energy supply E_{trac} is then defined as:

$$E_{reuse} = E_{recov} * \eta_{regen} \tag{13}$$

The reused energy will replace energy supplied at the level of the tank/electrical outlet. How much energy that can be *saved*, E_{saved}, will depend on the drivetrain efficiency $\eta_{drivetrain}$ (tank to wheel/electric outlet to wheel) which we also assume constant over the drive cycle and thus:

$$E_{saved} = E_{reuse}/\eta_{drivetrain} \tag{14}$$

We approximate the engine-braking force with a friction power of 0.160 kW/rps in a 2-l gasoline engine [24,25].[3] Engine-braking will reduce the amount of energy available for regeneration and depends on driving style, e.g. in what situations the driver uses the clutch when braking and which gear is engaged. Because of this ambiguity, we discuss the potential for energy recovery in a mHEV on the basis of three stylized variants for the engine-braking loss. Case I: *No* engine-braking, corresponding to a car designed with automatic engine-clutching (and shut-off) during braking. Case II: The engine speed while braking, and therefore also the engine-braking power, is assumed *proportional to the vehicle speed* with an engine speed of 3000 rpm at 100 km/h. We can think of this as a situation in which the highest gear is always used in engine-braking. Case III: The same as Case II, but we assume a *constant* engine-braking power of 4.7 kW for speeds below 59 km/h; given the assumptions above, this corresponds to an engine speed of 1761 rpm, which is our estimated average engine speed for a 6-gear car when engine-braking in the NEDC test cycle. A constant engine-braking power could correspond to engine-braking with a suitable gear following the speed. Case III thus results in higher engine-braking power than Case II at speeds below 59 km/h. In all three cases, the weight of the regeneration equipment itself has been assumed to be negligible.[4] A 50 kg weight increase would on average correspond to about 2.2% increased total loss at the wheels.[5]

2.3. Individual car movements

We use GPS logs of individual movement patterns for 378 privately-driven Swedish cars, each tracked for between 1 and 2 months during 2010–2012, with all seasons of the year covered [20,21]. These cars are up to 9 years old,[6] and the total cumulative distance driven is about 880,000 km. The participants were recruited by mail from a randomly drawn stratified selection of car owners from the Swedish vehicle register. Position, speed, and altitude were logged 2.5 times per second, which allows for investigating the power and energy fluxes at the wheels. The positioning data are used together with the Swedish National Road Database to determine how large a share of the drive cycle is in urban areas.

Some quality aspects of the measured position data with a focus on the altitude has been assessed by comparing the loggings from two country-side road sections frequently driven in both directions to reference road altitude data from the Swedish Transport Administration [29]. The main errors in altitude (standard deviation of typically 2–3 m), originating from differences in atmospheric conditions, were found to vary only slowly in time and space. We have found that these errors occasionally could add power levels of around 1 kW to the drive cycle while typically adding power of around 0.1 kW and should therefore not affect our main results to any larger extent. Changes in satellite constellation of the measurement introduce insignificant errors; the standard deviation for adjacent points in time was 127 mm compared to 123 mm for non-changing constellation. Rapid error changes can also be a result of signal reflections in nearby structures such as building in cities but these have not been evaluated.

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

[3] The engine-braking assumption is based on an older 2-l engine; newer car engines are often a smaller size and have a lower specific friction, which would lead to a lower level of engine-braking.

[4] Fuel economy in hybrid electric vehicles is less sensitive to changes in mass compared to conventional vehicles [26–28].

[5] It would also increase the braking energy somewhat (4.1% on average), and assuming a two-way regeneration efficiency of 50%, the increase in total energy losses at the wheels due to the extra weight could be reduced to 1.6%.

[6] Nine years is close to the economic lifespan of the car and thus the usage pattern of older cars are of less interest.

The data are filtered to reduce and remove errors from signal reflections and other possible noise in the measurement that could lead to an overestimation of the available braking energy. First, data collected under bad signal conditions are removed. Then, speed and altitude cycles are filtered through a low pass filter to exclude noise resulting from the limitations in measurement accuracy and logging frequency. Acceleration/deceleration and road gradient at time *t* were derived from the filtered speed and altitude cycles at *t* ± 1 and finally unrealistic values at this stage were also filtered.[7]

GPS-equipment needs time (often about 30 s) at the beginning of each trip to find satellites before logging can begin, so the first start-up phase of each trip is at risk of being missed. Therefore, an estimated speed cycle with moderate acceleration up to the first logged speed value is added to prevent a systematic underestimate of the total energy use.

The annual driving for each movement pattern is derived from a scaling of the measured driving period to one year. The individual measurement periods are distributed reasonably evenly across seasons from 2010 to 2012. Some of the cars have a large share of driving during a holiday period, while others have none.

3. Results

3.1. Potential for brake energy regeneration

The regeneration potential will depend on the size and distribution of the energy loss. Fig. 1 depicts (for our assumed car) the individual total energy loss at the wheels per km of driving. For the average drive cycle,[8] the loss averages 0.12 kW h/km, ranging from 0.10 up to 0.16 kW h/km for individual drive cycles. The total energy consumption per km is relatively independent of the average velocity of the vehicle.[9] The greater energy loss from air resistance with greater speed is largely counteracted by less braking with greater speed. Specific braking energy varies by about a factor of six among individual movement patterns, ranging from around 0.014 to 0.087 kW h/km, with an average of 0.033 kW h/km, corresponding to 27% of the total average loss.[10] Ignoring the altitude profile reduces the calculated average braking energy by 14% to 0.029 kW h/km. The braking energy on the NEDC cycle is about 0.034 kW h/km and a bit higher for the WLTP cycle, 0.037 kW h/km.

The share of energy at the wheels lost through braking varies between 10% and 61%, with an average of 27%. This average is comparable to the test cycles; the NEDC and the suggested WLTP test cycles lose 29% and 27% on average, respectively, for our normalized car. Even though test cycles are designed using data from real-world driving, they will unavoidably introduce flaws into the regeneration analysis by assuming flat roads. For the movement patterns used here, neglecting the altitude profile decreases the average share of braking energy to 23% of the total energy at the wheels. Thus the test cycles give a higher share of energy lost through braking; this is further discussed in connection to Fig. 4.

The powers P_{acc}, P_{grade}, and P_{roll} are proportional to the mass (see Eqs. (2), (3), and (5)) and thus the corresponding energies E_{acc}, E_{grade}, and E_{roll} are also proportional to the mass. P_{trac} is proportional to P_{acc}, P_{grade}, and P_{roll}, respectively, but also to P_{air}, and therefore the elasticity for P_{trac} with respect to mass will be dependent on P_{air}, which will depend on the driving. For our

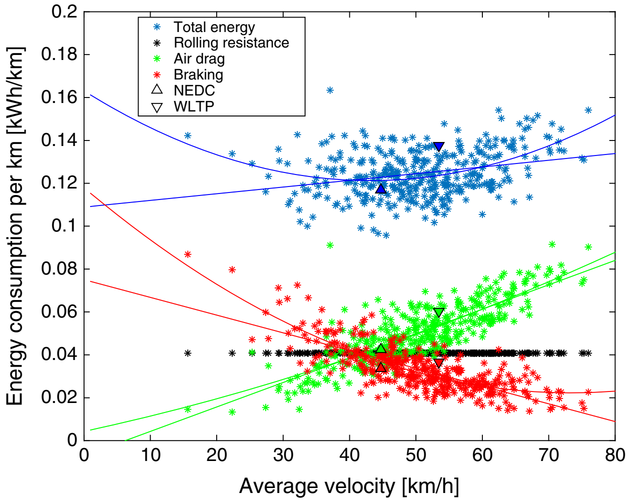

Fig. 1. For the assumed midsize car, for each movement pattern (asterisks: individual vehicles in our data; triangles: test cycle values, see legend), the average energy at the wheels (components: rolling resistance, air drag, and braking) lost per km of driving and its components, as a function of the average velocity. Solid lines correspond to linear and quadratic regressions.

dataset, the average elasticity for E_{trac} with respect to changes in mass is 0.66, ranging from 0.42 to 0.93 (to a large extent dependent on the average speed of the driver). Also, the elasticity of E_{brake} to changes in mass will vary (since $E_{brake} = E_{trac} - E_{roll} - E_{air}$), with an average elasticity of 1.23, ranging from 1.06 to 1.48.

Analogously, P_{roll} and P_{air} and hence E_{roll} and E_{air} are proportional to the rolling friction coefficient and C_dA value, respectively. The elasticity of E_{trac} with respect to C_dA is 0.34 (ranging from 0.067 to 0.58), and with respect to c_r it is −0.26 (−0.18 to −0.34). The elasticity for E_{brake} with respect to C_dA is −0.23 (−0.057 to −0.47) and with respect to c_r it is −0.28 (−0.17 to −0.41).[11]

The cumulative distribution of road grades in the data set can be seen in Fig. 2. Not taking into account the altitude profile leads to an underestimate of the energy loss, especially the energy lost through braking. The average total energy loss at the wheels (E_{trac}, no energy regeneration assumed) increases by 5% when the road grade is considered, while the braking energy increases by 23%, Fig. 3. However, this estimate is performed by simply adding/removing an altitude profile to the given speed profile, but the speed profile depends on the altitude profile. What looks like braking in the speed profile could very well be an ascent. Also, a steady speed could mean that the driver is braking while going downhill. It is easy to see the importance of including road grade in an analysis of the regeneration potential from real-world driving, but it is difficult to say unambiguously how much energy these drivers would lose in a real situation through braking if these roads were flat. Wood et al. find that the contribution of road grade to simulated energy use in modern automobiles is (only) 1–3% of total fuel use,[12] compared to our 5% at the wheels [17]. But that estimate is at the tank after considering drivetrain efficiency and including standby loss and auxiliary loads. This generally lower loss percentage may to a large extent reflect the fact that the marginal traction efficiency is considerably higher than the average fuel efficiency in the fuel-propelled car.

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[7] Maximum allowed acceleration/deceleration is here limited to ±10 m/s^2, and maximum road grade is limited to 15%.

[8] This is an unweighted average of the individual drive cycles in the measured fleet. This applies to all fleet averages throughout the article.

[9] Speeds below 1 km/h are excluded in the average.

[10] Regression of specific braking energy with average speed, linear: $-0.00083X + 0.075$; quadratic: $1.8 \cdot 10^{-5} \cdot X^2$ $-0.0026X + 0.12$

[11] Corresponding elasticities for NEDC and WLTP are: for E_{trac} with respect to mass: 0.69 and 0.61, respectively; for E_{brake} with respect to mass: 1.16 and 1.20, respectively; for E_{trac} with respect to C_dA and c_r: NEDC: 0.31 and 0.29; WLTP: 0.39 and 0.24; for E_{brake} with respect to C_dA and c_r: NEDC: −0.16 and – 0.19; for WLTP −0.18 and −0.23.

[12] The average road grades in Woods et al. are similar to those in our measurements.

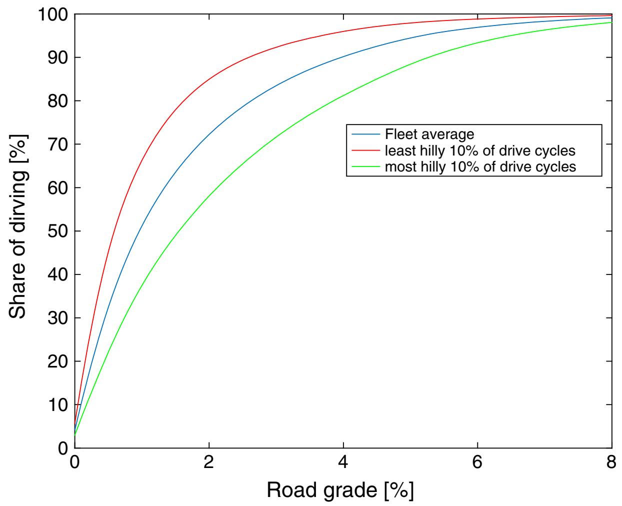

Fig. 2. For the measured drive cycles, the cumulative share of driving spent below a certain road grade (positive or negative).

Fig. 4 depicts how the braking energy loss per km depends on energy used to supply kinetic energy, potential energy, and the sum of both kinetic and potential energy. A regression where braking energy per km is set as the dependent variable, and kinetic and potential energy supplied per km are used as explanatory variables, yields a model where $Y = -0.022 + 0.83\ E_{kinetic} + 0.45\ E_{potential}$, with an $R^2 = 0.92$, up from 0.84 when only considering kinetic energy. In the test cycles, the energy needed per km for kinetic energy is within the range of our measured cycles. However, since the test cycles assume flat roads, they will in total have a lower level of energy spent on conservative energy needs compared to the measured drive cycles (Fig. 4c). However, the resulting energy lost through braking is also within the range of the measured drive cycles, which then results in a higher share of the conserved energy being lost through braking compared to the measured drive cycles. For the measured drive cycles, on average 40% of the energy used for kinetic and potential energy is lost through braking, spanning from 23% up to 63% for individual drive cycles. This is low compared to the test cycles, where 73% (NEDC) and 58% (WLTP) of the energy used for kinetic energy is lost through braking. The higher share of conservative energy lost through braking can be explained by the test cycles having a lower share of their deceleration taking place at high speeds, and they thus use a lower share of the conserved energy for overcoming air drag. For our drive cycles, the average share of conservative energy available at speeds under 50 km/h is 40%, while for NEDC and WLTP it is 67% and 50%, which partly compensates for the expected lower level of braking energy per km due to flat roads.

Which type of driving tends to have the highest amount of braking energy? From Fig. 1 we noted that vehicles with low average speed correlate positively with a high amount of braking energy per km. This also holds for the test drive sub cycles, which are included in Fig. 5a. A high share of city driving can be seen to correlate with a high amount of energy lost through braking per km, see Fig. 5b.

For the total yearly loss of braking energy there is, however, no clear correlation with the braking energy per km, Fig. 6a. On the contrary, drivers with very high shares of energy lost through braking are clearly not reaching the highest yearly energy savings. Instead, the total yearly distance driven seems to be more important for estimating the total yearly braking energy, Fig. 6b, even though the yearly distance driven correlates poorly with the *share* of energy lost due to braking. A city driver with a high yearly distance driven would probably reach a very high amount of braking energy on a yearly basis, but in our data the city driver is more likely to drive a relatively short yearly distance. We can here also note that scaling the calculated braking energy per km for the test cycles (red and green lines) by the yearly distance driven gives a fairly optimistic estimate (+31 and +42%, respectively, for NEDC and WLTP) of the yearly braking energy compared to the fitted average of the measured data (black line). For some drivers, the scaled yearly braking energy for the test cycles is three times as high as for the real driving.

How large a share of the braking energy that can be harvested through regeneration depends to a large extent on the power limitations of the electric components in the drivetrain. Fig. 7a shows the probability distribution for the power levels involved in braking, for each movement pattern, and 7b shows the cumulative likelihood of the braking power being less than a given power level. This gives an indication of the power requirements of any regeneration equipment; on average, 10 kW will cover almost 77% of the available braking energy (E_{brake}) for the drive cycles in the data set (ranging from 60% to 90% for the individual vehicles), while 40 kW will on average cover close to all braking energy (99%). The solid black and the dashed black lines depict the average for the 10% of the vehicles with the lowest and highest average

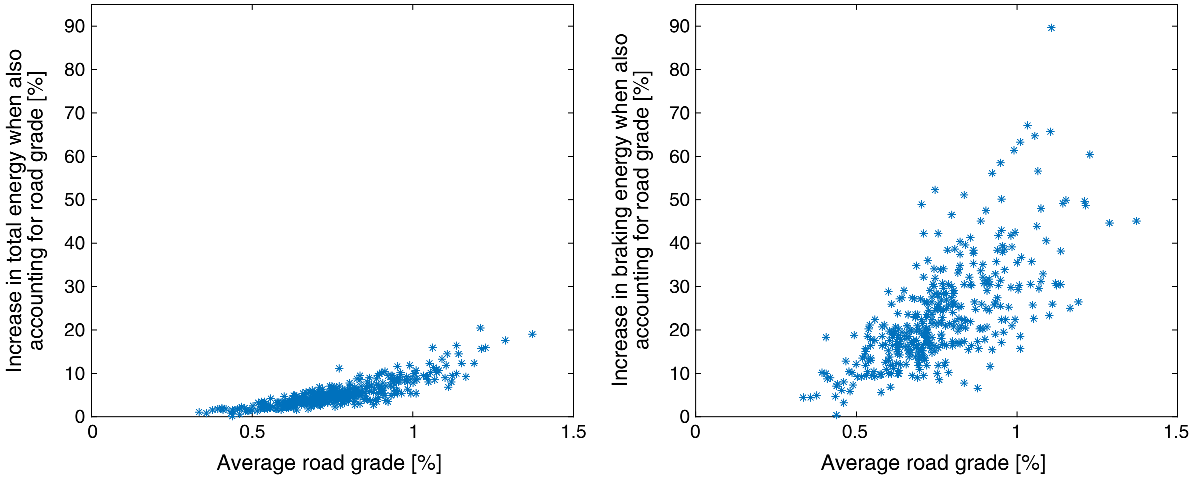

Fig. 3. For individual drive cycles, (a) the increase in total energy loss at the wheels, and (b) the increase in braking energy at the wheels when the individual altitude profile is added.

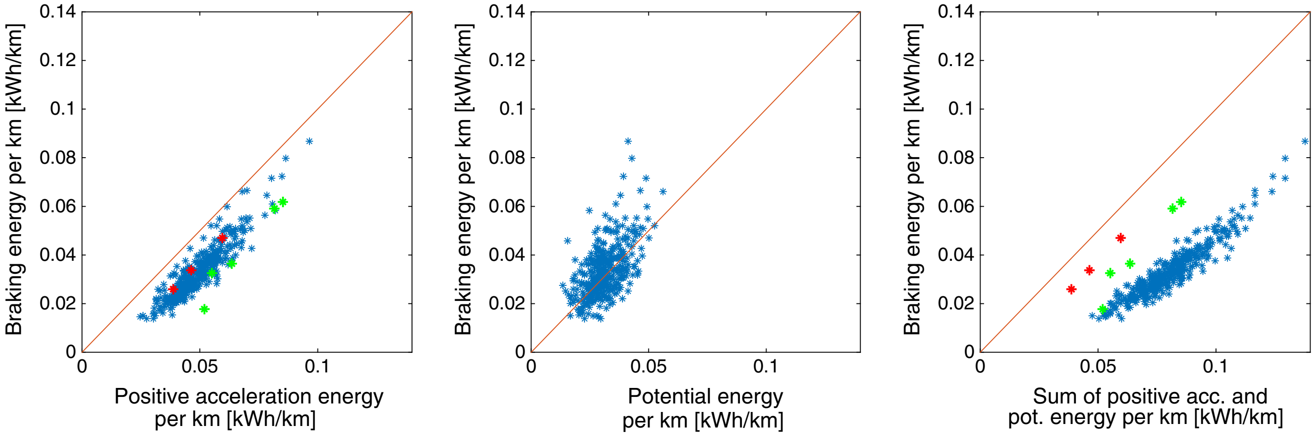

Fig. 4. For the assumed car, for each movement pattern, the average energy lost through braking per km as a function of, (a) the average supplied kinetic energy per km, (b) the average supplied potential energy per km, (c) the sum of supplied kinetic and potential energy per km. Included are also from left to right the values for NEDC (red dots): ECE, weighted average, EUDC, and WLTP (green dots): low, middle, weighted average, high, extra high, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

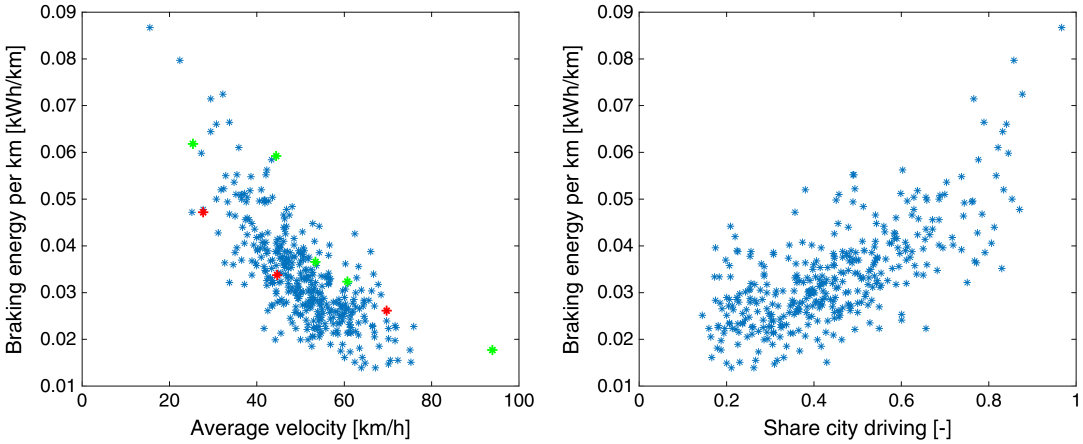

Fig. 5. For the assumed car, for each movement pattern, (a) the average energy lost through braking per km as a function of the average velocity; (b) the average energy lost through braking per km as a function of the share of driving conducted in urban areas. Included in (a) are also from left to right the values for NEDC (red dots): ECE, weighted average, EUDC, and WLTP (green dots): low, middle, weighted average, high, extra high, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

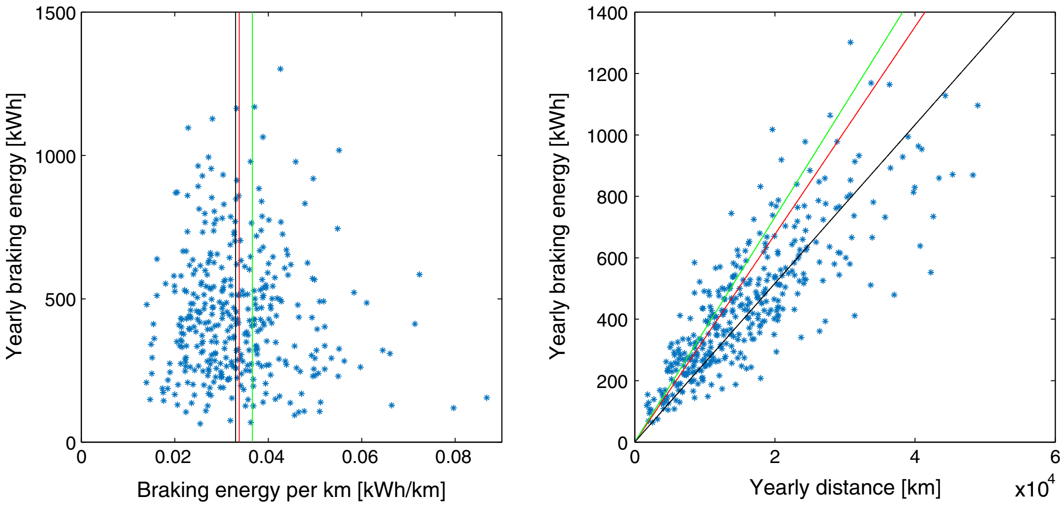

Fig. 6. For the assumed car, for each individual drive cycle, the yearly total energy loss at the wheels through braking as a function of (a) the average braking energy loss per km, (b) the yearly mileage. The red and green lines represent the NEDC and WLTP test cycles, respectively. The black line in (a) represents the average braking energy per km; the black line in (b) represents a one-dimensional fit to the data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

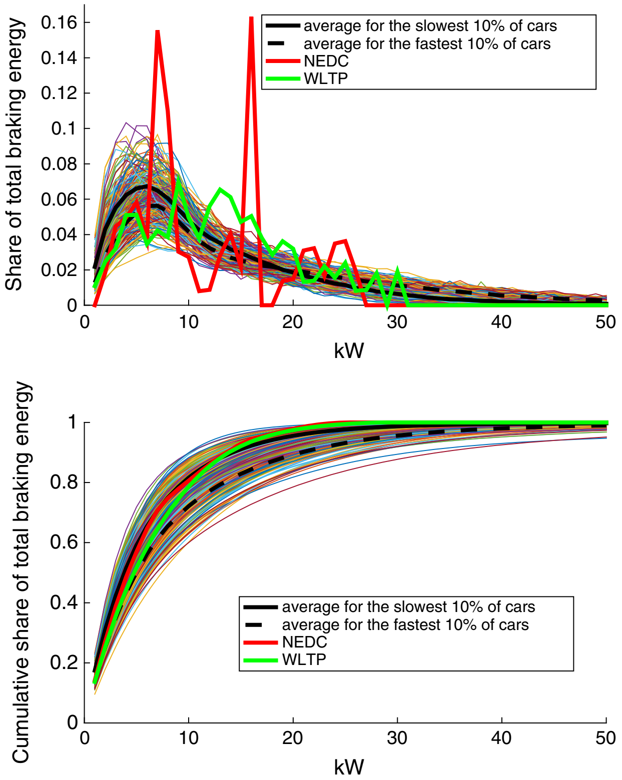

Fig. 7. For the assumed car and for each movement pattern, the probability distribution of the power levels involved in braking (a) and the cumulative likelihood that the braking power is less than a given power level (b).

velocities, respectively. The cars that are driven at higher speeds generally have a larger share of braking taking place at higher power levels than for cars with lower average velocities. NEDC and WLTP test cycles include relatively few working points, hence their jagged curves in Fig. 7a. The small number of working points increases the possibility for car manufacturers to optimize their drivetrain on the specific test cycle. The cumulative share of total regeneration for both the NEDC and WLTP lies above the slowest 10% of the vehicles in the data set for power levels above 13 kW and do not include any braking in power levels above 30 kW, Fig 7b. The range of cumulative share of braking energy between individual drivers is however rather narrow (at 10 kW the NEDC and WLTP test cycles cover 80% and 79% respectively, which is only a bit higher than the average for the data set).

3.2. Practical energy recovery and savings

The share of the braking energy that can be recovered depends on the specific design of the drivetrain. To roughly illustrate what is achievable in practice, we investigate two drivetrains, a “battery electric vehicle” (BEV) and a “mild hybrid” (mHEV). The drivetrain assumptions (e.g. maximum power and efficiency in regeneration), as well as the resulting average regeneration potential and savings, are given in Table 1.

As already seen in Fig. 7, the average share of recoverable energy (E_{recov}/E_{trac}) for the assumed BEV is very close to the case with no power limitations, since there is almost no regenerative energy to gain from an increase in maximum regeneration power above 40 kW. As discussed earlier, a majority of the braking-energy is already available at below 10 kW (76%, Table 1), making the difference in share of recoverable energy small between the BEV and the mHEV without engine-braking. In both cases with engine-braked mHEVs, the recoverable energy is roughly halved due to the energy loss through engine-braking. In the case of a speed dependent engine brake (Case II), on average 43% of the braking energy is lost to engine-braking, Fig. 8, reducing the recoverable energy from 76% to 42% of the total braking energy. The loss is somewhat higher for the third case, on average 57%, thus reducing the recoverable energy from 76% to 32% of the total braking energy. As expected, the loss is especially high for drivers with low average speed.

Table 1
Assumptions, average regeneration potential and yearly savings for the four exemplary drivetrains.

		BEV	mHEV Case I no Engine Brake	mHEV Case II Engine Brake proportional to speed	mHEV Case III Engine Brake proportional to speed above 59 km/h, constant below
Regeneration power limit		⩽40 kW[a]	⩽10 kW[b]	⩽10 kW[b]	⩽10 kW[b]
Regeneration speed limit[c]		⩾5 km/h	⩾5 km/h	⩾5 km/h	⩾5 km/h
Regeneration two-way efficiency, η_{regen}[d]		0.64	0.5	0.5	0.5
Drivetrain efficiency, $\eta_{drivetrain}$ (tank to wheel/electric outlet to wheel)		0.8[e]	0.3[f]	0.3[f]	0.3[f]
Charger efficiency		0.94[g]	–	–	–
Share brake energy	E_{brake}/E_{trac}	0.27			
Share recoverable energy	E_{recov}/E_{trac}	0.26	0.20	0.12	0.09
	E_{recov}/E_{brake}	0.99	0.76	0.43	0.32
Share reusable energy	E_{reuse}/E_{trac}	0.17	0.10	0.06	0.04
	E_{reuse}/E_{brake}	0.63	0.38	0.21	0.16
Yearly energy savings at the wheels	E_{reuse} (kW h)	278	166	94	72
Yearly saved energy at electric outlet/ tank	$E_{saved} = E_{reuse}/\eta_{drivetrain}$ (kW h)	237	553	313	239

[a] Approximately the same as the Nissan Leaf.

[b] In the mHEV, engine-braking may also occur, so regeneration can only occur after the engine-braking power loss.

[c] Using regenerative braking at very low speeds is problematic (The low rotational speed of the wheels increases the need for torque, which makes regeneration less efficient or impossible if demanding a higher torque than the generator can provide.) and braking conducted at speeds below 5 km/h is therefore deducted in the recoverable energy. This lowers the recoverable energy from 76.88% to 75.74% and from 98.98% to 97.85% for the 10 and 40 kW limits, respectively.

[d] The combined efficiency in charging the battery and later discharging for use.

[e] From [30].

[f] Marginal drivetrain efficiency for a conventional car (Since the engine will many times be running in parallel with the electric machine, a marginal efficiency will give a conservative energy savings estimate.

[g] From [23].

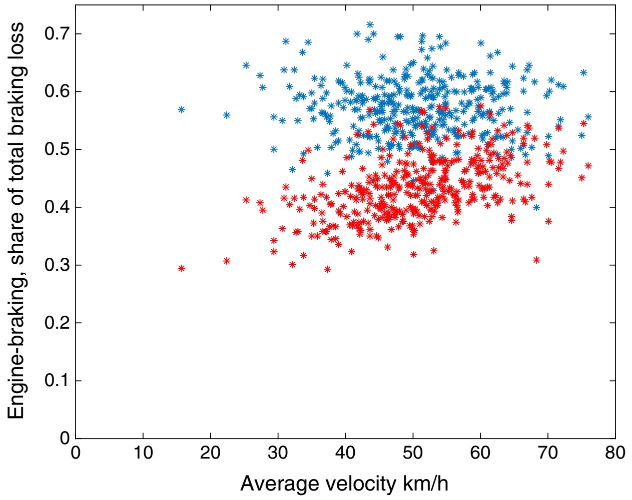

Fig. 8. For each individual movement pattern the share of engine-braking of total braking energy available with a 10 kW regeneration system, for Case II (red) and for Case III (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

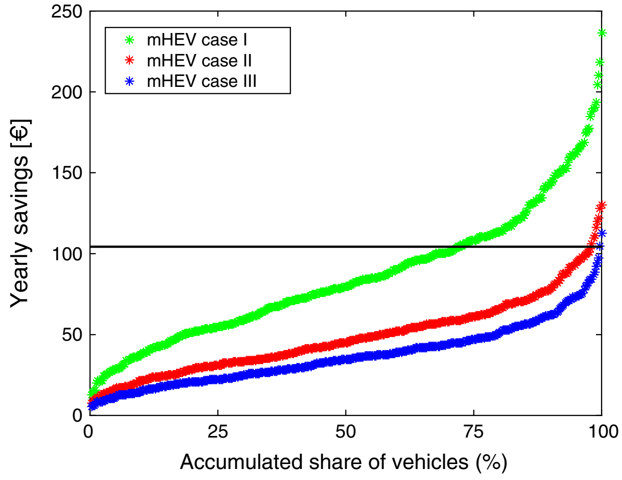

Fig. 10. For the modelled mHEV drivetrains cases estimated yearly monetary savings from reduced fuel use by regeneration (assuming regenerated energy replaces gasoline and a gasoline price of €1.5/l); together with an annuitized investment cost for turning a conventional car into a mHEV (black line). Note: each curve is sorted independently.

The brake torque distribution between front and rear axle is important for the vehicle stability [31]. Limiting the braking torque on the front axle to 70% in cases of a brake retardation above 1.5 m/s^2 will on average reduce the regeneration potential with 6% (spanning from 2% to 12% for individual drive cycles).

The yearly energy savings will depend on a potentially costly regeneration capacity, and it is therefore interesting to study the expected yearly savings both on the margin (Fig. 9a) and in total (Fig. 9b). The marginal savings from extra generation capacity are strictly decreasing and the more foot-braking (less engine-braking), the higher the marginal gain. The drivers who drive the most miles per year can save about four times as much energy at the tank compared to the 10% of drivers who drive the fewest miles per year.

The potential yearly energy savings at the tank for the mHEV can be twice as high as in the BEV case at the electric outlet because of the low efficiency of the conventional drivetrain, see Table 1, although, we also have to note that it is different forms of energy saved. Engine-braking can bring these values down to be on par with the BEV, though. The yearly energy savings in the mHEV roughly corresponds to about 57, 32, and 25 l of gasoline per year for the three variants of engine-braking respectively. Assuming a gasoline price of €1.5 per litre (roughly the current price in Sweden) the average savings from reduced fuel use can be estimated as 86, 48 and 37 € per year respectively. Following a cost model for mHEVs with engine-braking developed by [32] using data from [33,34], a 10 kW mHEV could today be expected to cost €695 extra compared to a comparable conventional car. Assuming an annuity of 0.15 (corresponding to for instance an annuity loan over 8 years with an interest rate of 5%), the extra investment would be covered if the yearly savings amount to 104 € per year. The average Swedish driver does not reach the

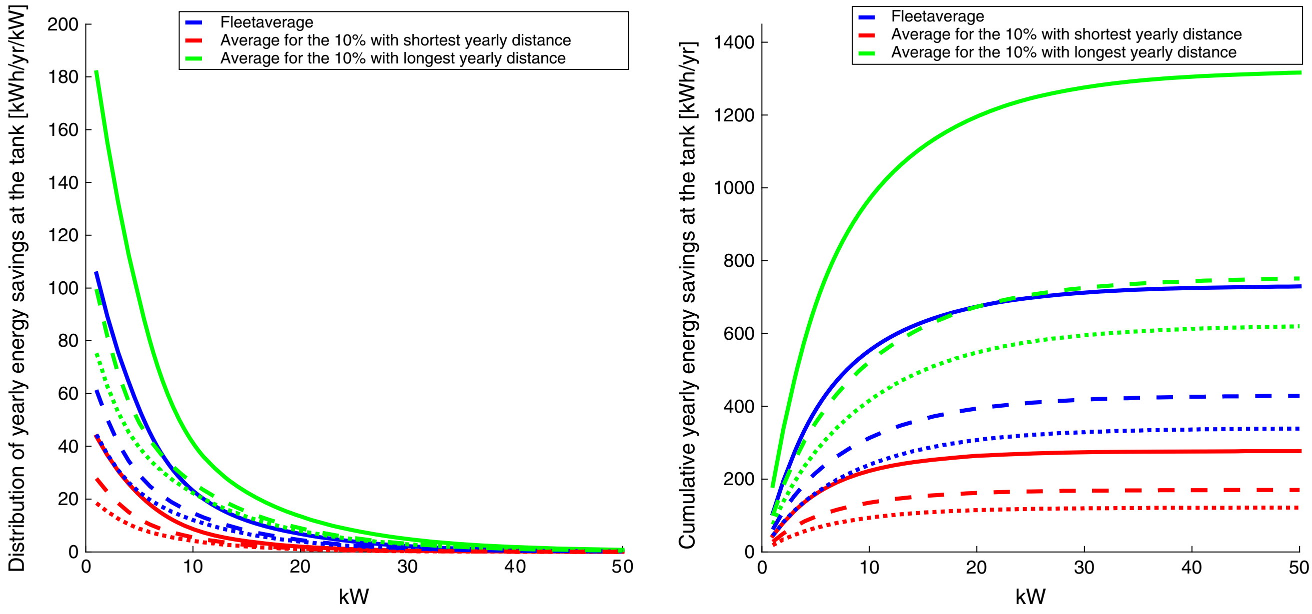

Fig. 9. For the modelled drivetrains (solid line: mHEV Case I, dashed line: mHEV Case II, dotted line: mHEV Case III) (a) the distribution of average yearly energy savings at the tank; (b) the average cumulative yearly energy savings at the tank.

needed yearly savings in any of our three mHEV cases, but there are some drivers who do, see Fig. 10. For the cases with engine braking (Case II and III) only 0.5–2% of the drivers manage to reach high enough yearly savings while about 28% can manage in the no engine brake case (Case I). It is likely however that the cost of €695 is calculated for a system with engine braking and the investment cost for Case I would therefore probably be higher. However, there are additional benefits of the hybrid system beyond the regenerative braking, not included here, such as fuel savings by engine stop/start at idling.

4. Discussion and conclusion

Evaluating the possible energy savings from brake energy regeneration is key to understand the energy-efficiency progress in transportation. This study uses a simple car model and individual drive cycles collected from real-world driving to estimate energy loss through braking and the corresponding regeneration potential for privately driven cars in Sweden.

Often, adapting a more eco-friendly driving style can reduce energy lost through braking, but this has not been taken into account in this model; instead, all measured drive cycles are used without any assumed adjustments in driving style.

Braking energy per km was found to vary with about a factor of six in between individual drivers. The question of which drivers actually benefit the most from regenerative braking is important in terms of environmental impact and driver economics. Earlier studies have shown a higher energy recovery per km for cars driving under urban conditions with low average velocity and many starts and stops. Our results confirm this but also point out that a low average velocity and a high share of city driving are not the major parameters determining the yearly energy savings; the yearly mileage is a more important indicator. This suggests that drivers who rack up the miles should be targeted as potential early adopters of regenerative technologies rather than city drivers per se.[13]

The results show the importance of including road grade in analyses of the regeneration potential in real-world driving. However, in terms of potential energy regeneration the NEDC and WLTP test cycles perform quite well in that the braking energy per km is similar to the average for Swedish driving. (Even though, as mentioned earlier, the measured Swedish driving also has available braking energy due to driving in a non-flat landscape. This is however compensated by higher losses from aerodynamic drag due to higher average speed when braking.) In terms of braking power, though, our results show that the test cycles best match the slowest cars in our data set. Discrepancies in braking-power profiles between test cycles and the real movement patterns can be problematic if new car models are optimized for, and evaluated on, test cycles while the real-world driving performance is significantly different.

The expected extra efficiency gains from higher regeneration power capacity fall off quickly, and a 10 kW mild hybrid is enough to capture on average almost three quarters of the energy available for regeneration for the assumed standard car.

The potential for brake energy regeneration has in this work been approximated as the amount of braking energy lost at the wheels. As discussed there are in reality several factors that may reduce the amount of available energy and the regeneration potential is thus to be considered as an upper potential.

To illustrate what level of energy savings that could be expected in practice we did a rough estimate of the savings for a BEV and a mHEV drivetrain. Our model for practical energy recovery, reuse and savings is in some aspects simplistic. This was done to reach a transparent model that facilitates a focus on the differences in regeneration potential between individual drive cycles from our data set. Our findings indicate that regeneration of braking energy under current Swedish driving conditions could increase energy efficiency, with average energy savings at the wheels of about 15% for a battery EV and up to 10% for a "mild" hybrid. At the electric outlet/fuel tank, the energy savings are up to twice as large for the mHEV (550 kW h/yr) compared to the BEV (240 kW h/yr), as a result of the less efficient drivetrain in the former. The yearly energy savings at the tank was found to vary with about a factor of four between the 10% of drivers with longest yearly distance compared to the 10% with the shortest yearly distance (and the individual variation was here even higher see Fig. 10).

However, we find that engine-braking in the mHEV could reduce the realizable regeneration by as much as 50%. This suggests large potential benefits from a drivetrain with effective engine decoupling and shut-off. On the other hand, recent improvements in lowering the specific friction and the trend towards smaller engine volumes ("downsizing") and lower average engine speed ("down speeding") would temper that figure somewhat.

Finally our economic estimate indicate that under current Swedish conditions, the economic savings from using less fuel due to regeneration will for most drivers not be sufficient on their own to offset the estimated investment cost of hybrid technology. But higher fuel costs, a higher price on carbon or other emissions regulations, as well as technology developments, could obviously change this. There are also other aspects of hybrid technology not considered in this study, for example energy savings by engine stop/start ability, which will contribute to it's economic viability.

Acknowledgment

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