Influence of the Driving Style on CO_2 and Pollutant Emission of Hybrid Electric Vehicles

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Introduction and measurement setup

In this paper influences from the driving style on the fuel consumption, on CO2 and on air pollutant emissions for hybrid electric vehicles is presented.. The underlying research project had a runtime from 9/2010 - 7/2013, was funded by the Austrian Klima- und Energiefonds and was part of the program NEUE ENERGIEN 2020, project no. 829966. Multiple publications already referred to the work [Blassnegger 2012] [Haberl 2014] [Kies 2013-02] [Wyatt 2012], the overall results are given in the final report [Kies 2013-11].

For conventional Diesel- and gasoline vehicles fuel-efficient driving strategies are investigated since the 1980ies, e. g. see the meta study [Wengraf 2012]. For hybrid passenger cars the manufacturers already offer information about an economic driving style, e. g. [Kmiecik 2013] [VW 2012]. Concerning the driver's behaviour the most important points are

- Take the bus, i. e. buy and use an additional vehicle only when necessary
- Smooth driving style without high acceleration
- Operate the vehicle in favour at constant speed
- Forward looking behaviour, e. g. coasting in front of red signals or stop signs
- Braking with coupled engine, then no fuel is consumed in towed operation
- Early upshift to keep the engine speed low
- Turn off the engine during stand-still
- Turn off electrical consumers like A/C and audio system, when not necessary

Most of these points are also valid for hybrid electric vehicles. In the research project it was investigated, if there are additional options, especially for heavy duty hybrid vehicles like city buses. In the whole work also simulations of the hybrid vehicle, the traffic flow at different driving styles and the battery wear, plus a calculation of the payback period of hybrid busses were conducted. This paper concentrates on the measured change of CO2 and air pollutants, all other results are described in the final report [Kies 2013-11].

The two measurement vehicles were both parallel hybrids, i. e. the electrical machine is mounted on the gearbox input shaft. The first vehicle was a city bus 12 m, model Volvo 7700 LH[1], and the second vehicle a sedan passenger car, model Volkswagen Jetta Hybrid[2].

As measurements instrument the PEMS (Portable Emission Measurement System) was used. It consists of an exhaust flow meter, model Sensors Semtech-EFM-HS, and a mobile emission analyser, model Sensors Semtech-DS. For this project the output for the emission mass flows of carbon dioxide (CO2), nitrogen oxide (NOx), hydrocarbons (HC) and carbon monoxide (CO) and the vehicle velocity was relevant.

[1] model year 2010, curb weight 12.2 t, Diesel engine EEV 4.8 L 161 kW, battery Li-Fe-P 4.9 kWh, electrical machine 70 kW_{mech}, 12 gear AMT
[2] model year 2013, curb weight 1.5 t, Otto engine EURO VI 1.4 L 110 kW, battery Li-Ion 1.1 kWh, electrical machine 20 kW_{el} (motor) 28 kW_{el} (generator), 7 gear double clutch gearbox

Methodology and Results - city bus

The bus with the mounted PEMS and ballast for the measurement is shown in **Figure 1**.

Figure 1: Exhaust flow meter (left), emission analyser (middle), ballast (right) [Blassnegger 2012]

Volvo signals the driver the max. recuperation limit of the electrical machine, when running as generator, with a soft arrestor at 20 % of the brake pedal position (position value according to CAN-Bus output). Until here all of the braking power is provided by the electrical machine, running as generator, and thus a high share of brake energy is recuperated. When actuating the pedal with more than 20 %, the wheel brakes are turned on and waste power as lost heat to the environment. To measure separately the influence of accelerator- and brake-pedal position, fix arrestors were built under the pedals to limit the actuation. Then the bus was measured on the test track at the Magna facility in Graz-Thondorf on an artificial bus cycle. The measurement cycle and the results are described in **Figure 2**.

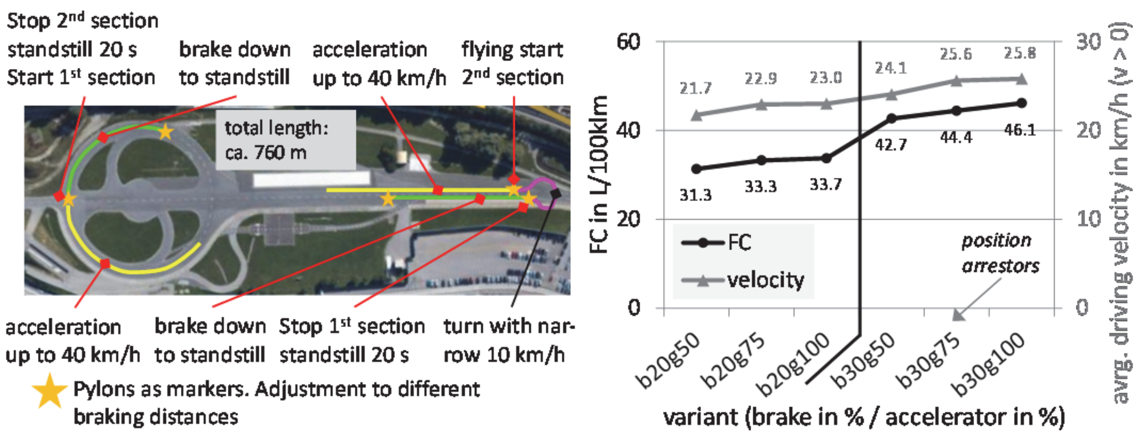

Figure 2: Measurement cycle and results, bus on test track. Payload 3.8 t [Kies 2013-02] (b20g50 means for example 20% brake pedal position in deceleration phases and 50% gas pedal position during acceleration)

It is obvious, that the maximum brake pedal position affects the fuel consumption more than the maximum accelerator pedal position. The reason is, that above 20 % pedal position the wheel brakes are actuated and brake power is lost. This effect is shown in Figure 3.

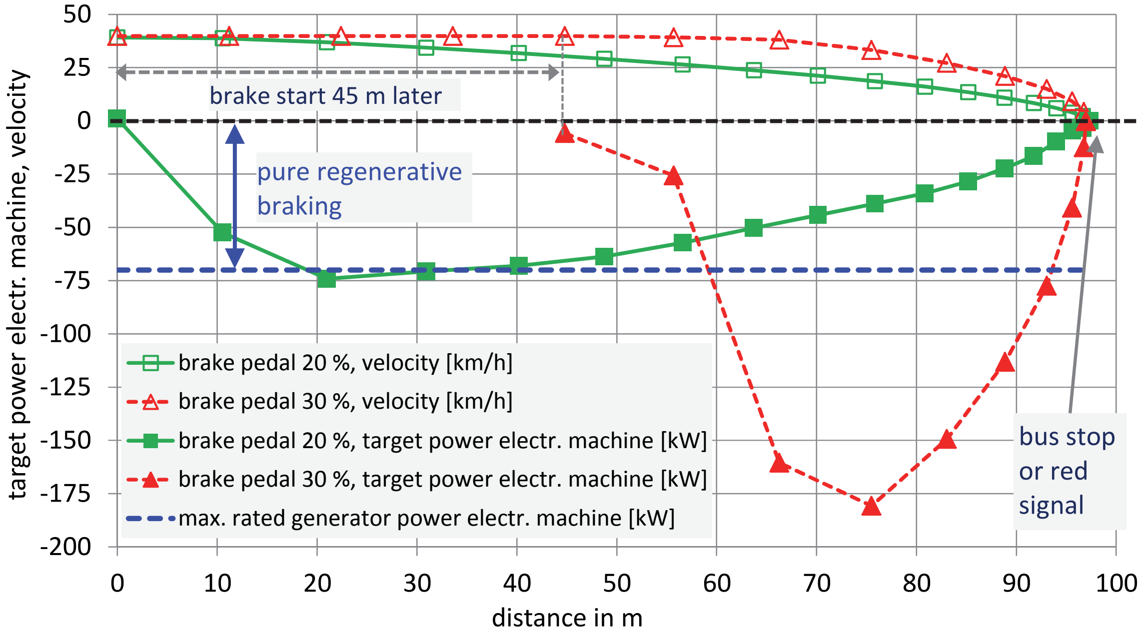

Figure 3: Target generator power at electrical machine for brake pedal position 20 % and 30 % with a payload of 3.8 t.

When driving towards a bus stop and actuating the brake pedal with 30 %, the driver can maintain the higher speed for 45 m longer than for cautious braking and win a few seconds in comparison, but causes losses of ca. half of the braking power in the wheel brakes. With pure regenerative braking almost no brake power is lost. This figure shows also the influence of the maximum generator power of the electrical machine: The higher it is, the more braking power can be recuperated at a speedy driving style. It shall be mentioned, that the average payload of a city bus during the day is not 3.8 t but ca. 1.2 t, according to German public transportation association VDV. So the power loss during harsh braking will be reduced for a lighter bus, because the absolute braking power will be smaller. But the principle remains: If the braking power exceeds the maximum generator power of the electrical machine, power will be lost in the wheel brakes as waste heat.

With this knowledge a driver training was conducted at Graz public transportation company HGL (Holding Graz Linien). 5 newly hired drivers should drive an 11 km lap in Graz with the hybrid bus, for the first time "as they like" and for the second time, after a theoretical and practical training in Hybrid-Ecodrive, with emphasis on regenerative braking. As driver aid a signal was mounted at the driver place, where the green light during braking showed a "good" behaviour, where all of the brake energy could be covered by the electric machine. The test round and the signal are shown in Figure 4.

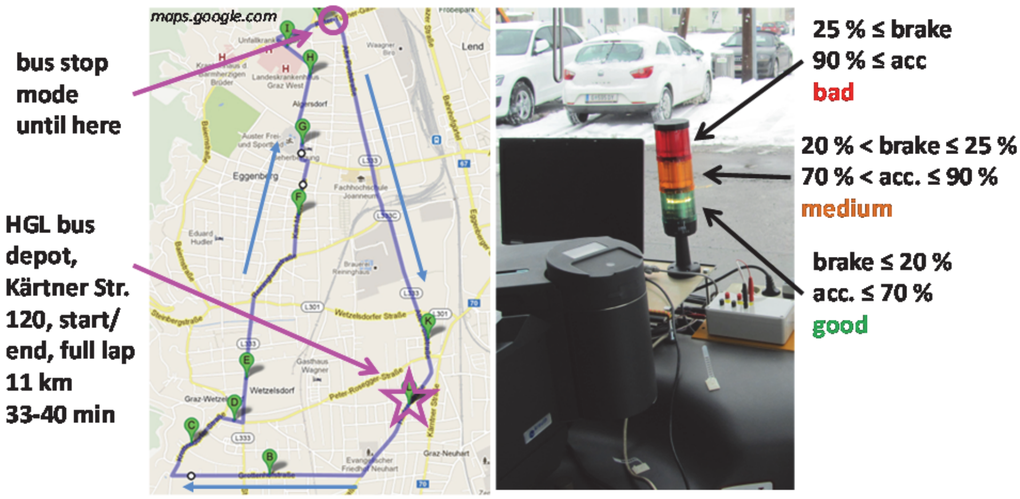

Figure 4: Test round in Graz for the driver training, and the pedal signal [Kies 2013-11]

The results of the measurement are given in **Figure 5**.

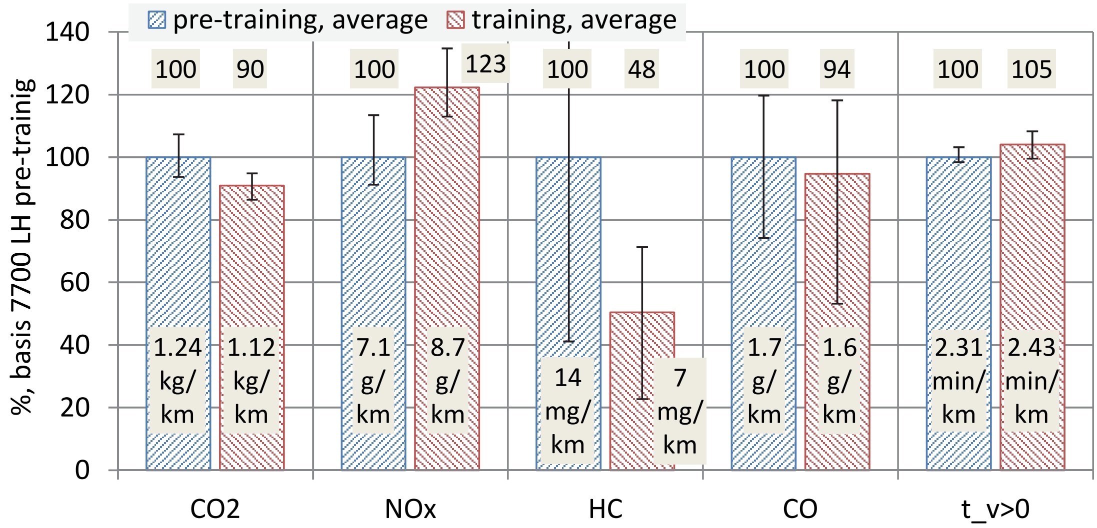

Figure 5: Results for the bus driver training, average of 5 drivers. Emissions CO2, NOx, HC and CO, average driving time per kilometre (v > 0, without stand-still). Payload 0.8 t. [Kies 2013-11]3

The bus drivers were asked to accelerate quick, to meet the timetable, but to try to brake with 20 % pedal position to recuperate as much energy as possible. The result is a reduction of FC and CO2 emissions of 10 %, also the pollutant emissions HC and CO decreased by 48 % and 6 %.

The average driving time (v > 0) increased only slightly by 0.12 min/km. This means, that on a bus line with 20 km length the driving time, without stand-still, will increase by ca. 2.5 min, what seems to be a practicable compromise between fuel saving and lap duration. So the Ecodrive could be implemented without changing the timetable, because a few minutes delay are already considered.

The reason for + 23 % NOx emission is the setting of the bus, that during regenerative braking the Diesel engine is idling in decoupled state, see Figure 6.

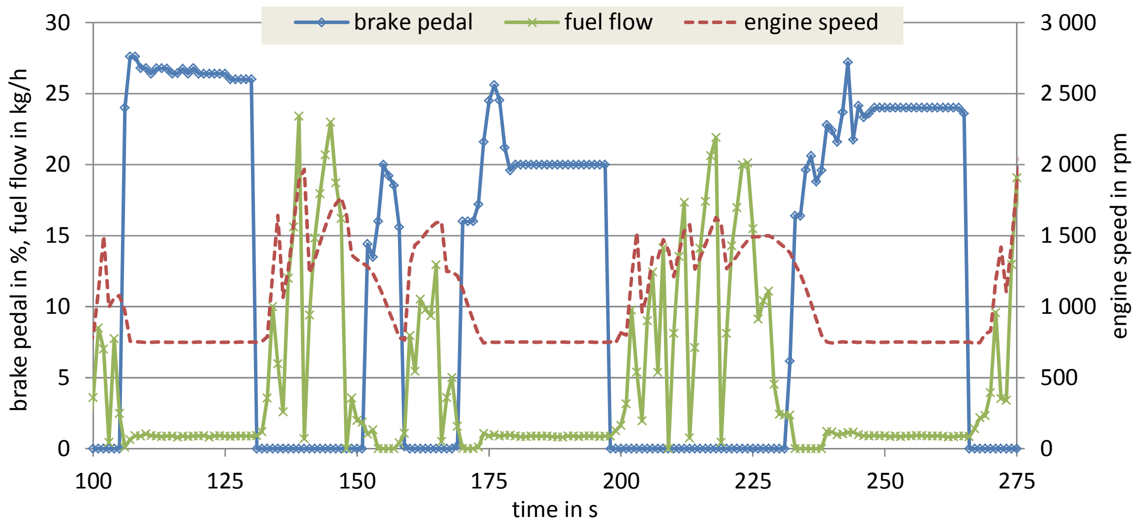

Figure 6: Engine idling during regenerative braking [Kies 2013-11]

This causes at Ecodrive a higher amount of comparatively cool idling exhaust gas, flowing through the exhaust aftertreatment system (EAT) which cools down the SCR system.

[3] The fuel consumption (1 L_{Diesel}/100km =1 kg_{CO2}/km * 38 [(L_{Diesel}/100km)/(kg_{CO2}/km)]) with 0.8 t payload on the road is high when compared with the results from the test track with 3.8 t payload. In both cases A/C and heating were turned off. The reason could be different ambient conditions or different settings of the measurement instrument. In any case the relative change in the results from one driving style to another in one measurement setting is depicted correctly.

So the average exhaust gas temperature at Ecodrive training is lower, see **Figure 7**

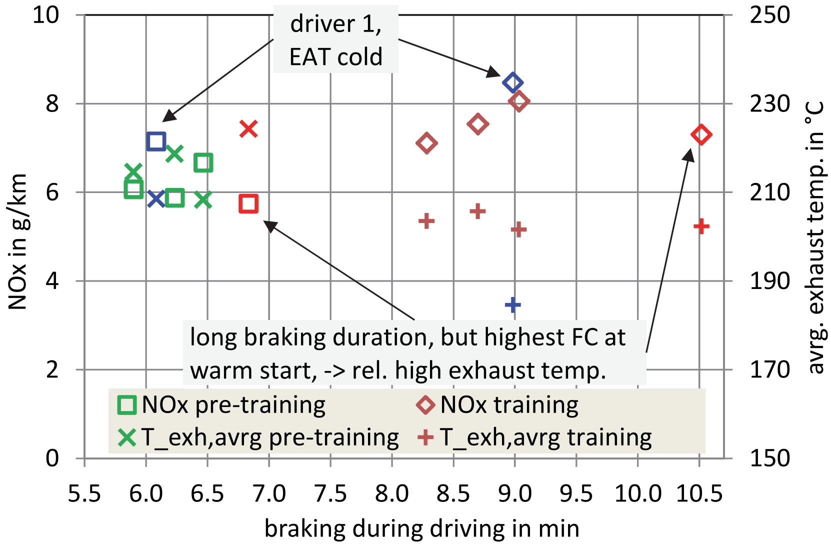

Figure 7: NO_x emission, average exhaust temperature and braking duration, dependent on driving style [Kies 2013-11]

This leads to the effect, that the conversion rate of the SCR catalyst is lower.. The higher the catalyst temperature, the higher is the conversions rate for NOx and the lower the tailpipe emissions are.

It has to be noted, that hybrid vehicles may also shut down the engine during braking (typical in passenger cars). This leads to zero mass flow through the SCR system and helps to keep the SCR on a reasonable temperature level.

It shall be remarked, that the measurement vehicle was of emission standard EEV. With the introduction of EURO VI the absolute pollutant emission decrease significantly, as shown e.g. with a measurement of a EURO VI Microhybrid bus in the final report [Kies 2013-11, p. 20].

Methodology and Results - Passenger Car

The sedan was also equipped with the PEMS. For this vehicle the information about the recuperation potential is shown to the driver by a power-meter as round instrument, see **Figure 8**.

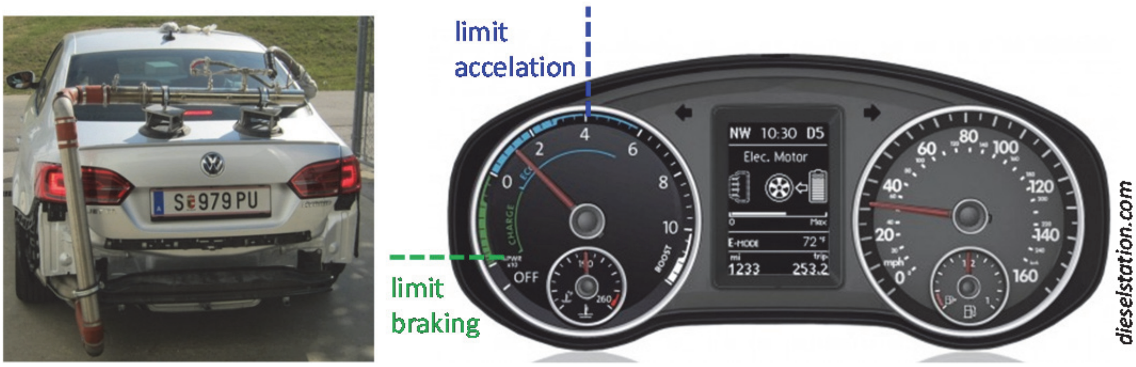

Figure 8: Sedan passenger car with mounted PEMS, power-meter with limits for Ecodrive [Kies 2013-11]

The lower end of the green area of the power meter marks the maximum generator power of the electrical machine. The drivers were asked to drive a short round in the university quarter of Graz, the first time with their individual driving style and the second time with regard to the acceleration and braking limits on the power-meter. The results are shown in **Figure 9**.

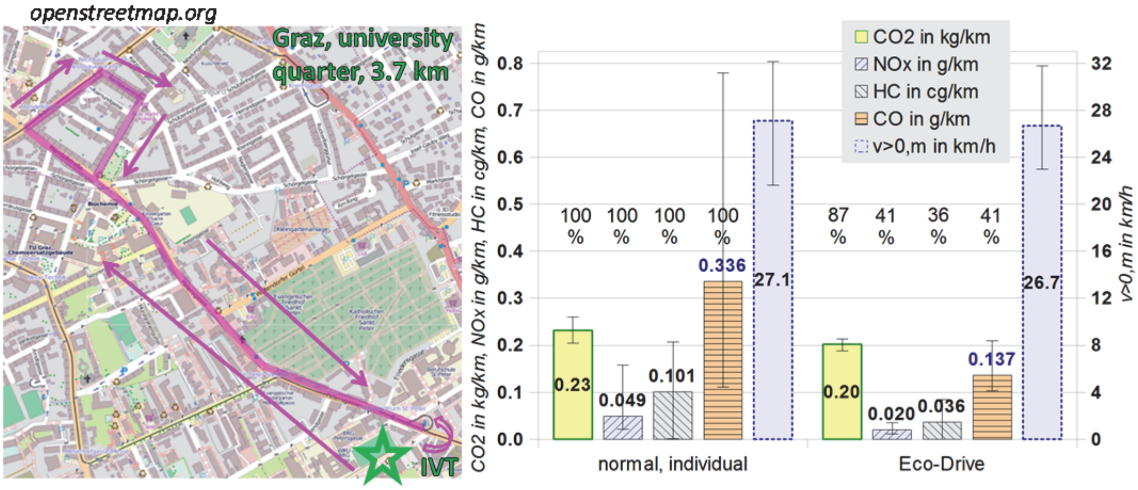

Figure 9: Test round for passenger car, and results, average of 7 drivers. Payload 0.35 t [Kies 2013-11]

For the passenger car FC and CO2 decrease at Ecodrive for 13 %, and each pollutant emission for ca. 60 %. Interesting is, that the average driving velocity (without stand-still) decreases very little from 27.1 km/h to 26.7 km/h. So there is nearly no time loss due to the Ecodrive.

But it is necessary to know that the mass-specific recuperation power of the passenger car is much higher than in case of the bus. The passenger car offers ca. 30 kW_{mech} recuperative braking power for a vehicle mass of ca. 1.7 t, in case of the bus the relation is 70 kW_{mech} to ca. 13.5 t average vehicle mass. So the car drivers do not need to brake extra-cautiously to recuperate much braking power

Summary

In this paper the correlation between the driving style and CO2- and pollutant emissions for electric hybrid vehicles is analysed. In terms of fuel consumption and CO2 an adapted driver behaviour allows a reduction of 10 % and more, where the emphasis is on gentle, longer braking. So the generator power of the electrical machine is not overstressed and nearly all braking power can be recuperated without actuating the friction brakes at the wheels, which cause only lost heat.

In case of pollutant emissions of the city bus with Diesel engine analysed, emission stage EEV, HC were reduced by 52 % and CO by 6 %. NOx increased by 23 %, because during the longer braking phases, where the engine idles, relatively cool idle exhaust cools down the SCR catalyst and thus decreases its NOx conversion rate at later driving phases.

For the passenger car equipped with an Otto engine of emission stage EURO 6, the Ecodrive decreased NOx and CO by 59 % and HC by 64 %. For this vehicle no increase of emissions at Ecodriving could be observed.

The combination of gentle braking, depending on the maximum generator power of the electrical machine, with a speedy acceleration allows an Ecodrive which extends the driving duration only marginally. This is especially important for city buses, which need to follow a prescribed timetable.

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