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Design and realization of a One-Pedal-Driving algorithm for the TU/e Lupo EL

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Abstract

Since 2011 the Eindhoven University of Technology (TU/e) is using an in-house developed battery electric vehicle based on a Volkswagen Lupo 3L for educational and research projects. The TU/e Lupo Electric Lightweight (EL) is able to recuperate kinetic energy by using regenerative braking. A brake pedal based regenerative braking strategy demands applying a combination of hydraulic and regenerative brake force. A proper control of this brake blending proves to be challenging. An advantage of an electric vehicle compared to an ICE car is that substantial amounts of deceleration can be achieved without applying the friction brakes. These observations have led to the concept of One Pedal Driving (OPD) where the accelerator pedal can also be used to perform regenerative braking. A similar concept is applied in for example the BMW i3 and Tesla Model S and is rated quite positively by drivers. Since kinetic energy cannot be recuperated with 100% efficiency, for some driving conditions the best thing to do is neither propel nor brake the vehicle and just let the car roll freely, which is known as coasting. During coasting minimal energy is used which improves the overall energy efficiency. To assess regenerative braking strategies that are currently applied in electric vehicles, a selection of vehicles has been investigated. These vehicles are subjectively evaluated by driving tests on public roads where special attention is paid to the regenerative braking and coasting characteristics. Before designing a suitable OPD algorithm, a list of requirements is composed. The overall motor performance limits are investigated and based on the OPD requirements a general accelerator pedal map is designed and implemented. Based on a limited number of driving tests, subjective and objective conclusions regarding energy efficiency and drivability are drawn. The tests with various drivers indicate a slightly improved driving efficiency. Furthermore, all drivers comments positively on using OPD as being very intuitively and are able to adapt to it quickly.

Keywords: Regenerative braking, One-pedal-driving

1 Introduction

1.1 TU/e Lupo EL

In 2009 the Dynamics and Control group of the TU Eindhoven (TU/e) started the development of battery electric vehicle, using a VW Lupo 3L as donor vehicle [1]. In the beginning of 2011 the vehicle obtained a permit from the Dutch roadworthiness authorities to drive on public roads and it was presented to the public. Since that time various research projects have been executed.

Figure 1: Lupo 3L with the existing diesel and new electric powertrain.

Figure 1 gives an impression of the exchange of the powertrain, from diesel to battery electric. An important characteristic of the vehicle is the large battery capacity (27 kWh $LiFePO_4$) in comparison to the vehicle dimensions and mass (1060 kg). This is also the reason why the vehicle is named TU/e Lupo EL, with EL being the abbreviation of Electric Lightweight. It results in a range that fairly easily exceeds 150 km and over 230 km has been driven on a single charge under favorable conditions [2].

Next to the physical exchange of the powertrain, a lot of effort has been put into developing control software, from the start-up logic, safety provisions, traction control, dashboard, etc. This paper discusses the changes to the control software that affects the behavior of the accelerator and brake pedal, which have resulted in a major improvement of the driving experience and an improved energy efficiency.

1.2 Powertrain and braking control

A schematic layout of the powertrain is given in Figure 2. The driver commands are passed through a Programmable Logic Controller (PLC) to the inverter. This allows to use and investigate different algorithms and combine information from different sensors.

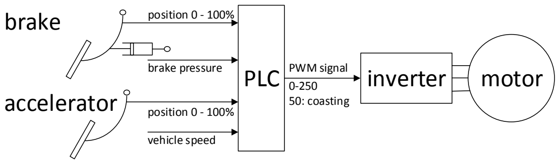

Figure 2: Schematic layout of the powertrain of the TU/e Lupo EL.

An advantage of electric vehicles is the possibility to harvest energy during braking, which would otherwise be transformed into heat by the friction brakes. At the start of the development of the vehicle the aim was to make it behave like a conventional car having an Internal Combustion Engine (ICE). This meant that regenerative braking on releasing the accelerator was very moderate and brake blending was performed when applying the brake pedal. Initially this was done using a pressure sensor in the braking system, thereafter the brake pedal travel was used to control the magnitude of regenerative braking. This second option allows harvesting somewhat more energy, as part of the initial brake pedal travel is used to increase the regenerative braking action without the friction brakes being applied. Also tests have been done on low friction surfaces, which made clear that whenever ABS becomes active, regenerative braking should be switched off completely. For more details see reference [3].

Nevertheless it was felt that the powertrain behavior could be improved. Upon touching the brake pedal, regenerative braking is switched “on”, without being able to exactly control the amount of deceleration. Also the accelerator pedal was judged to be “too aggressive” at low speeds, not allowing the driver to position the car exactly at the desired location. When the accelerator pedal is not carefully applied, the accelerations are high and uncomfortable and will most likely contribute to additional tire wear. Furthermore the vehicle was made to creep when the accelerator pedal is not applied, this was built-in to mask the free-play on the throttle pedal, which is used for regenerative braking. In section 3.3 a more detailed explanation on this phenomenon is given.

1.3 Motivation for OPD and coasting

The powertrain of an electric vehicle is fundamentally different from that of an ICE car and does not have to be operated by the driver in exactly the same way. Engine braking on an ICE vehicle is moderate and the accompanying vehicle deceleration is dependent on the gear selected, whereas with an electric motor and fixed reduction, very high and consistent levels of deceleration can be achieved. Nevertheless the friction brakes still are present, as they are legally required.

These observations have led to the concept of One Pedal Driving (OPD) where the accelerator pedal can also be used to perform regenerative braking to a certain level without the need to use the brake pedal and application of the friction brakes. This concept is applied for example in the BMW i3 and Tesla Model S and is rated quite positively by the drivers. They describe the car as being “glued” to their right foot and are quite positive about being able to control the vehicle with one foot [4-6].

In the Lupo EL the friction brake system is unmodified with respect to the donor vehicle, which limits the possibilities for brake blending. Furthermore it can be noticed that the brake pedal feel in some hybrid production cars is not optimal which may lead to a loss of driver confidence [7]. By separating the application of regenerative braking and friction brakes, the brake blending strategy can be simplified.

Although regenerative braking has clear advantages over application of the friction brakes, one should also beware that converting kinetic energy to electric energy and its storage in the battery and vice versa is not 100% efficient. If we assume the efficiency between the battery and wheels to be 80%, then only 64% of the energy captured by regenerative braking, will available at the wheels at a later stage.

This leads to the concept of “coasting”. For some driving conditions the best thing to do is neither to propel or brake the vehicle, and just let the car roll freely with minimal energy usage from the battery [8]. This concept is not only used on electric vehicles, but is also applied on some ICE passenger cars and trucks [9]. In these cases the clutch is opened to allow the vehicle to roll freely. In electric vehicles the implementation of “coasting” may vary from car to car, as will be discussed in section two.

1.4 Outline of the paper

The remainder of this paper is organized as follows: first a number of test drives have been made with various electric vehicles and our impressions are described in section 2. The design criteria and actual development of a One Pedal Drive (OPD) algorithm is discussed in section 3. After implementation in the TU/e Lupo EL, various driving tests have been executed with different test drivers. The analysis of the tests is described in section 4.

2 Driving tests with existing electric cars

To assess regenerative braking strategies that are currently applied in electric vehicles, a selection of vehicles is investigated that are popular in the Netherlands. This selection consists of: Tesla Model S, Renault Zoe, BMW i3, Mitsubishi Outlander PHEV and the Volkswagen e-Up! The vehicles are subjectively evaluated by driving tests on public roads. In particular attention is paid to the driver control of regenerative braking and coasting. The observations from these tests will be used to define a list of design requirements for the OPD design, as will be discussed in section 3.1.

2.1 Tesla Model S

When driving the Tesla Model S, it is clear that the accelerator pedal characteristics have been designed with One Pedal Driving in mind. Fully releasing the accelerator pedal results in a maximum available regenerative braking power of 60 kW and a notable vehicle deceleration. At higher velocities the Model S can conveniently be driven without having to use the brake pedal and friction brakes. By retaining a constant accelerator pedal position it is possible to put the powertrain in a coasting mode, though this requires a very precise operation of the accelerator pedal and attention of the driver.

When the vehicle velocity decreases below 21 km/h, the ‘coast-position’ of the accelerator pedal is changing and it is gradually decreased to zero when standing still. This is also accompanied by a major reduction in the regenerative brake torque. Although in general releasing the accelerator pedal results in sufficient deceleration, it is nearly impossible to come to a full stop. When the velocity drops below 10 km/h, the regenerative brake torque appears to become zero, which results in the need for applying the friction brakes to bring the car to a full stop.

2.2 Renault Zoe

The regenerative braking strategy of the Renault Zoe is more focused on offering a driving behavior similar to that of a conventional ICE powered vehicle. Releasing the accelerator pedal therefore only results in a minor deceleration, effectively simulating engine drag. The majority of the regenerative braking torque is applied in parallel with the conventional brakes. Below 30 km/h, the regenerative torque available with a fully released accelerator pedal gradually fades to zero at 20 km/h and stays zero until the creep velocity of 8 km/h is reached. A driving torque is applied to retain this creep velocity.

Although for efficiency reasons this behavior could be beneficial as the vehicle is essentially coasting upon releasing the accelerator pedal, in practice it means that it is virtually impossible to move in low speed traffic without applying the friction brakes. Also the fact that the vehicle creeps results in the necessity of applying the friction brakes.

2.3 Mitsubishi Outlander PHEV

The Mitsubishi Outlander PHEV is essentially a hybrid, but can also be driven in a full electric mode. It is interesting because of its user configurable regenerative braking control. Using pedals behind the steering wheel, six different settings (B0 - B5) can be selected that control the level of regenerative torque that is available when releasing the accelerator pedal. In setting B0 zero regenerative torque is available when the accelerator pedal is released and the vehicle is coasting. In most conditions this behavior is not very comfortable since it requires a very frequent use of the brake pedal. When driving with the highest regenerative braking setting (B5), a substantial amount of deceleration can be achieved when releasing the accelerator pedal.

Although the deceleration can be controlled fairly well, coasting is very hard to achieve and requires maintaining a very precise accelerator pedal position. With decreasing velocity, starting at 30 km/h, the regenerative brake force is gradually reduced up to the point where the vehicles starts rolling freely which is around 10 km/h. Hereafter the vehicle remains its creeping velocity of 6 km/h. The regenerative braking behavior of the Outlander PHEV allows driving without using the brake pedal for the majority of driving situations. However, because the vehicle creeps (which cannot be disabled) and because the regenerative torque is decreased to zero below 10 km/h, it is impossible to drive the vehicle with the accelerator pedal only in normal traffic.

2.4 Volkswagen e-Up!

The Volkswagen e-Up! is a battery electric vehicle which has similar dimensions as the TU/e Lupo EL. The e-Up! offers the ability to choose multiple regenerative braking levels via the gear selection lever. In normal traffic, only setting ‘B’ allows driving with the accelerator pedal only. However, since the regenerative torque diminishes when the vehicle speed drops below 5 km/h, a somewhat more defensive driving style is required to come to a full stop without using the brakes. With respect to coasting, in none of the regenerative braking settings the driver is able to easily coast the vehicle. Finding the pedal position that lets the vehicle coast is almost impossible, because of the high sensitivity of the accelerator pedal for these conditions.

Considering the creeping behavior, an interesting concept has been applied in the e-Up! When driving off, the vehicle velocity increases fairly vigorously to a creep velocity of about 5 km/h. The brake pedal has to be applied to bring the vehicle to a stop. However after exceeding a velocity of 8 km/h, the creeping mode is switched off and the vehicle is able to come to a full stop without application of the brake pedal. When the accelerator pedal is only slightly touched, creeping is switched on again. This switching creep functionality is considered to be annoying by some drivers. The possibility to come to a full stop without brake pedal application has a positive effect on drivability.

2.5 BMW i3

In the BMW i3, the concept of One-Pedal-Driving has been applied in its full extend: in normal traffic applying the brake pedal is simply no longer required. As one of the few vehicles that has been tested, the i3 manages to come to a full stop without using the brake pedal in nearly all normal driving conditions.

Furthermore the level of deceleration that can be achieved by maximum regenerative braking is made velocity dependent. At higher velocities the BMW i3 clearly has a lower deceleration when fully releasing the accelerator compared to lower velocities. In most of the other vehicles examined, the maximum deceleration appears to be nearly constant. The maximum deceleration above

100 km/h is estimated to be approximately 0.75 m/s^2 and below 60 km/h it is estimated to be in the range between 1.25 and 1.75 m/s^2. The BMW i3 does not creep.

The characteristics of the accelerator pedal of the BMW i3 are designed with coasting capabilities in mind. When driving at a certain speed, slightly lifting the accelerator pedal puts the car in a coasting mode. Although the pedal travel where coasting is active is limited, especially at low and medium speeds, the progressive nature of the accelerator pedal makes it very easy to coast. Below 6 km/h coasting is not possible, but this is not experienced as being detrimental. In comparison to the other cars evaluated, the BMW i3 is rated by the drivers as having the most pleasant accelerator characteristics, allowing both true one pedal driving and convenient coasting.

3 OPD design

3.1 General requirements

After analyzing the limitations of the Lupo EL, studying existing electric cars and some reasoning the following list of requirements has been created.

- For normal driving conditions the driver should be able to control the acceleration and deceleration by the accelerator pedal only. Deceleration is done entirely via regenerative braking. The vehicle should be able to come to a full stop without using the brake pedal, e.g. controlled stop in front of a red traffic light.
- The driver is able to freely select the desired deceleration level, with the accelerator pedal not being overly sensitive and having sufficient travel to adapt the deceleration level.
- The brake pedal is only needed for emergency cases. For these rare conditions energy harvesting is considered not important and the friction brakes are used to achieve the desired deceleration. Regenerative braking may be gradually switched off, depending on the deceleration and ABS becoming active.
- There is no change in deceleration when releasing the accelerator and the first, initial application of the brake pedal.
- The vehicle does not creep at zero or low velocity. At low speed the sensitivity of the accelerator is such that the driver is able to adjust speed to any desired level.
- A coasting mode with minimal energy usage can be easily selected by the driver.
- The brake lights will be switched on when the vehicle deceleration corresponds to a brake application in a normal ICE car. High frequent flashing of the brake lights will be prevented.
- Switching off the cruise control will gradually introduce regenerative braking, thus giving the driver some time to apply the accelerator.
- When cornering at high lateral acceleration the level of regenerative braking will be reduced to ensure vehicle stability. In particular oversteer reactions of the vehicle should be prevented when suddenly releasing the accelerator pedal.

3.2 Inverter settings for OPD

Before focusing on the detailed Human Machine Interaction (HMI) aspects of One Pedal Driving, the overall powertrain limits have to be set, e.g. the maximum low and high speed acceleration and deceleration levels. They are controlled by parameters in the inverter software. The low speed acceleration is controlled by a current limitation in the inverter. It is selected such that on a dry road no wheel spin of the front wheels will occur. The high speed acceleration is limited by the peak power of the motor and the desire to have an acceptable 0-100 km/h acceleration time of approximately 13 seconds.

The required deceleration levels were determined by driving tests in regular traffic. It appears that a deceleration of 2 m/s^2 is more than sufficient to allow One Pedal Driving without having to use the friction brakes. At high speed the deceleration is reduced and controlled by a regenerative power limitation setting in the inverter software. When full regenerative braking is applied, a deceleration of approximately 1.5 m/s^2 at 100 km/h is obtained. Nevertheless for normal highway driving and highway exits this is still too much and the high speed deceleration will reduced further by the OPD algorithm.

It is interesting to note that the deceleration limits, which were determined by experiments, agree quite well with the extremes found in the acceleration profiles of various driving cycles, see Figure 3. So with the selected inverter settings the vehicle will be able to only use regenerative braking in nearly all driving cycles, which is beneficial for the energy consumption.

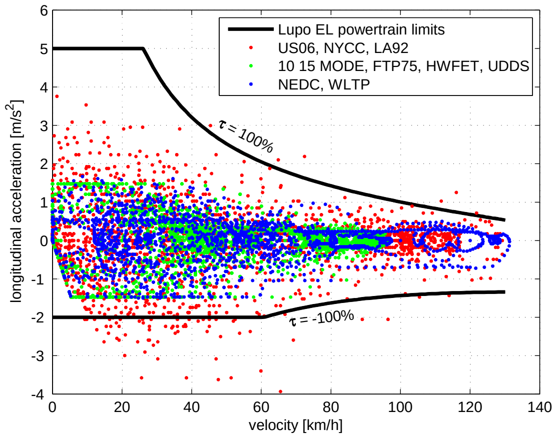

Figure 3: Comparison of Lupo EL powertrain acceleration limits and different driving cycles. (Green/blue: driving cycle completely within powertrain limits, red: some points outside)

3.3 OPD accelerator pedal mapping

One Pedal Driving is all about applying a positive or negative torque to the wheels with respect to the accelerator pedal position. The pedal position is indicated by the variable p, which is expressed as a percentage of the maximum accelerator pedal stroke. The motor torque request is expressed with the variable τ ; $\tau = 100\%$ would indicate maximum acceleration, $\tau = -100\%$ means maximum regenerative braking, as shown in Figure 3. When $\tau = 0\%$ no torque is applied and the vehicle is coasting.

A simple linear accelerator pedal map to apply a positive or negative motor torque to accelerate or decelerate the vehicle respectively can be seen in Figure 4. A major problem with this map is starting from standstill. The driver presses the accelerator pedal, but experiences free-play and the vehicle does not respond. Only by pressing the pedal further the vehicle will start to move. Since the transition point to driving is not exactly known, the driver may apply to much pedal resulting in an uncomfortable launch of the vehicle.

A trick to overcome this problem is to introduce vehicle creep, which effectively masks the free-play on the accelerator pedal. Creep does however not comply with the idea of One Pedal Driving because the friction brakes have to be applied to prevent the vehicle from moving. To avoid these limitations and to allow for example coasting, a more sophisticated accelerator pedal map will be developed.

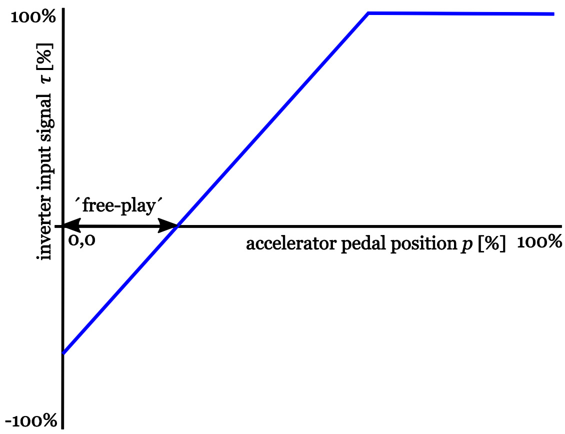

Figure 4: Linear accelerator pedal characteristic for applying regenerative torque.

3.3.1 Coasting

In order to provide the driver an easy selectable coasting possibility, an accelerator pedal range is defined, where the motor torque is zero ($\tau = 0\%$). On the other hand to circumvent the aforementioned free-play problem, this coasting range should be zero, when the vehicle is standing still.

Two velocity dependent coasting lines are defined, to describe the upper and lower boundary of the coating range accelerator pedal position. The upper line is defined as:

$$p_{cu} = \phi \left(\frac{v}{v_{\max}}\right)^{\frac{1}{m}} \quad (1)$$

The lower line is defined as:

$$p_{cl} = \phi \left(\frac{v}{v_{\max}}\right)^{\frac{1}{m}} - c_h \left(\frac{v}{v_{\max}}\right) \quad (2)$$

Where v equals the vehicle velocity, $v_{\max}$ is the top speed of the vehicle, ϕ determines the pedal stroke at top speed when a driving torque is applied, c_h equals the size of the coasting range at top speed. The variable m can be used to shape the characteristics.

These expressions are illustrated by Figure 5 and it can be seen that the coasting range and velocity dependency can be shaped in a flexible way. The coasting range increases linearly with forward velocity, which appeared to be sufficient based on driver feedback from various experiments.

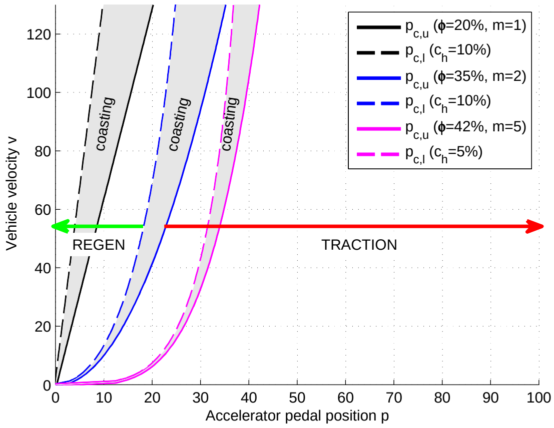

Figure 5: Possible definitions of the coasting range.

3.3.2 Regenerative braking

As already mentioned in section 3.1, the maximum deceleration that the Lupo EL can achieve at high velocities needs to be reduced. On the motorway a deceleration of 1.5 m/s^2 upon releasing the accelerator is simply too much and undesirable in regular traffic. Also at very low speeds regenerative braking of 2 m/s^2 is experienced as uncomfortable and too aggressive. These considerations have resulted in a velocity dependent definition of τ_{rm}, the maximum regenerative braking torque, expressed as a percentage. This is implemented in the PLC using a look up table, as is illustrated by Figure 6.

Furthermore the driver has to be able to control the amount of regenerative braking in the range between the fully released accelerator pedal and lower coast line p_{cl}. The following function is used for this purpose:

$$\tau_r = a_r p^{\psi} + b_r p + c_r \qquad (3)$$

Where p equals the accelerator pedal position and τ_r defines the amount of regenerative braking. The exponent ψ gives some control over the degree of non-linearity. The coefficients a_r, b_r and c_r can be calculated by taking into account the next three conditions:

$$\begin{aligned} \tau_r &= \tau_{rm} && \text{when } p = 0 \\ \tau_r &= 0 && \text{when } p = p_{cl} \\ \frac{d\tau_r}{dp} &= 0 && \text{when } p = p_{cl} \end{aligned} \qquad (4)$$

The last condition ensures a very smooth application of the regenerative brake torque, when the driver leaves the coasting range by releasing the accelerator pedal. The expressions above are illustrated by Figure 7.

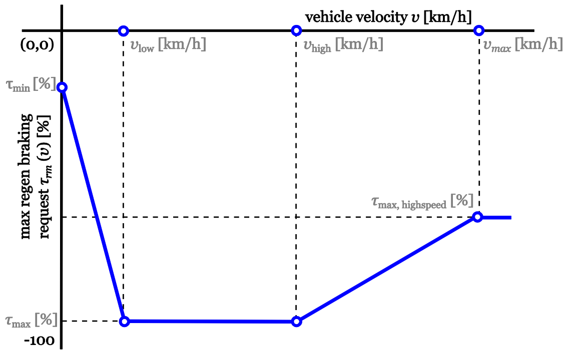

Figure 6: Fully released pedal characteristic.

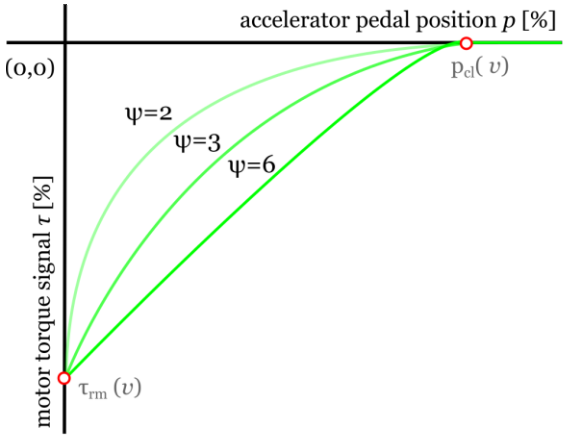

Figure 7: Regenerative braking characteristics.

3.3.3 Acceleration

In general an electric motor is able to apply maximum torque from standstill. The powertrain limits as defined in Figure 3 will easily allow the vehicle to accelerate with wheel spin under slightly less favorable conditions. Apart from potential safety issues, it will lead to increased tire wear. To limit the maximum torque that can be applied to the wheels at low velocities a lookup table is introduced that prescribes the maximum motor torque τ_{am} as a function of the vehicle velocity v. Still the driver can get 100% motor torque by using the kickdown option, which is activated when fully pressing the accelerator pedal. These characteristics are illustrated by the blue lines in Figure 8.

The accelerator position where the maximum motor torque τ_{am} becomes available is defined by the variable p_m. This avoids the need to fully press the accelerator pedal to achieve the maximum torque and it can be used to tune the sensitivity of the acceleration of the accelerator pedal. Again a look-up table is used to define p_m as a function of forward velocity, the red line in Figure 8 illustrates this characteristic. So to achieve maximum acceleration it is not necessary to use the full accelerator pedal stroke. Especially at low speeds this prevents the car from feeling sluggish, though the maximum acceleration that can be achieved by the vehicle does not change.

Similar to the regenerative braking part, a function is used to define the requested driving torque τ_a as a function of the accelerator pedal position p in the range between p_{cu} and p_m. The following function is used:

$$\tau_a = \left(\frac{p - p_{cu}}{p_m - p_{cu}}\right)^{\gamma} \tau_{am} \qquad (5)$$

In this expression the exponent γ can be used to make the characteristics somewhat progressive, which appears to be important at low speeds based on feedback from the drivers. It should be noted that p_m, p_{cu}, τ_{am} and γ are all dependent on the vehicle forward velocity v. The function used is displayed in Figure 9.

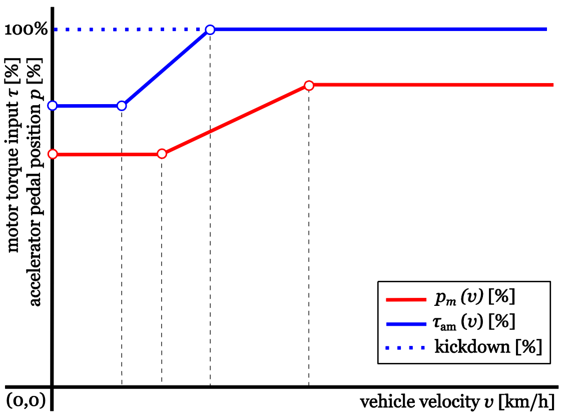

Figure 8: Maximum motor torque input and accelerator pedal position characteristics.

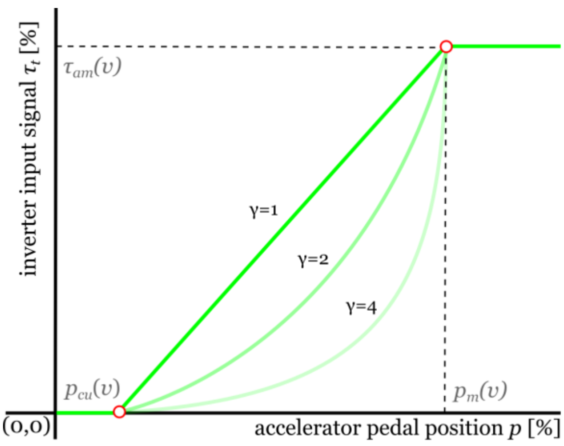

Figure 9: Traction motor torque signal

3.4 Vehicle acceleration map

After many test drives and various iterations a setting was found that felt "right" to the various drivers and which allows One Pedal Driving without using the friction brakes in normal traffic. Figure 10 shows the longitudinal acceleration a_x as a function of the accelerator pedal position p and vehicle velocity v on a level road and two people in the vehicle. Various aspects of the OPD algorithm can be observed: an area where coasting is possible, the maximum possible deceleration increases at lower forward velocities when the accelerator pedal is fully released, the pedal does not have to be applied 100% to achieve maximum acceleration. The line describing zero longitudinal acceleration ($a_x = 0$ m/s^2) is important as it corresponds to driving with constant forward velocity. It appears that for this condition the relation between accelerator pedal position and vehicle velocity is almost linear. This is a bit of a surprising result considering the complexity and non-linearity in the OPD algorithm and was not especially aimed for in the first place.

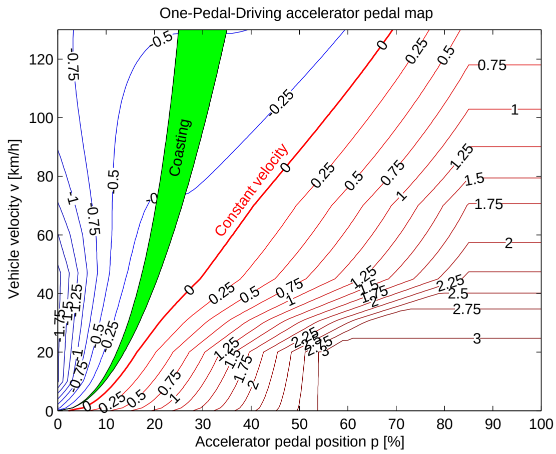

Figure 10: Accelerator pedal map showing the longitudinal acceleration a_x as a function of the accelerator pedal position p and the vehicle velocity v.

3.5 Controller enhancements

Although the development of an OPD algorithm primarily focusses on the accelerator pedal response, some other important aspects have to be taken into account. The first issue concerns the behavior of the braking pedal. For energy efficiency matters it does not make sense to increase the regenerative torque when applying the brakes since the algorithm has been designed with the idea that in normal traffic situations using the friction brakes is not necessary. In the rare occasions braking is required, energy efficiency is not an issue. To provide a reliable, predictable and safe braking behavior, upon the application of the friction brakes the regenerative torque will be kept constant and matches that of a fully released accelerator pedal. The additional deceleration is obtained by application of the friction brakes.

Another issue that has to be taken into account is the interaction of One-Pedal-Driving with the cruise-control. Switching off cruise-control will result in an immediate deceleration of the vehicle, because the driver does not have his foot on the accelerator pedal. To tackle this problem, after switching off cruise-control, the regenerative torque is slowly increased such that after 3 seconds the maximum amount of deceleration is available. During this period the driver is able to 'counteract' the increasing deceleration by pressing the accelerator pedal. Practice shows that drivers are being accustomed to this behavior very rapidly.

An important safety-issue that seems straightforward but should not be underestimated is the brake-light control (see [10]). As was made clear before, up to 2 m/s^2 deceleration can be achieved without applying the brake pedal (and thus no brake light). The most obvious way of switching the brake-light is based on the longitudinal acceleration a_x. The longitudinal acceleration is however influenced by road slopes and is therefore not the most suited. Another option is to use the motor current. The measured current signal however experiences a time delay with respect to the vehicle deceleration and is therefore also less suited. In the TU/e Lupo EL, a basic algorithm has been implemented that switches the brake lights based on the motor torque input signal τ and the vehicle velocity v. Designing a suitable algorithm however proved to be non-trivial. Additional research on this topic would therefore be very useful.

Although a basic regenerative braking controller is implemented in the TU/e Lupo EL that prevents the wheels from locking while braking regenerative, One Pedal Driving makes it even more important to incorporate a suitable regenerative control. As opposed to the brake based strategy, without operating the pedals a maximum amount of regenerative torque is exerted on the front-wheels which can be especially harmful when cornering. To cope with these situations the maximum amount of regenerative torque is limited as a function of the vehicle's lateral acceleration a_y.

4 Driving tests

In the preceding section an OPD algorithm has been introduced and explained. After obtaining a final set of parameters a series of driving tests were executed on the public road with different persons. These tests were executed on two fixed routes: urban driving through the center of Eindhoven and rural driving in the surroundings of Eindhoven. Highway driving was excluded because of the limited number of braking events. Each route was driven twice: once with the default accelerator map (combined with regenerative braking coupled to the brake pedal) and once with the OPD algorithm.

It should be mentioned that although both algorithms have been tested under the same conditions as much as possible, because of the relative short route even small variations in traffic conditions or driving style can have large influences on the driving efficiency. Moreover, to be statistically significant, much more tests under various conditions should be performed. Therefore one has to be careful with drawing definite conclusions based on this limited set of experiments.

4.1 Energy usage

The energy usage of the vehicle is determined by analyzing the power flow from and to the high voltage battery. When defining a positive power flow as depleting the battery, integrating this flow with respect to time will result in an upper, positive value for the energy consumption. Due to the regenerative braking a negative power flow will occur charging the battery again. Integrating this power flow results in the recuperated energy. To account for battery charging and discharging losses, it is assumed that 80% of the measured recuperated energy is available for traction again. The nett energy consumption thus equals the positive energy consumption minus 80% of the recuperated part.

The results for urban driving are shown in Figure 11. Looking at the results it can be concluded that overall a higher (7%) driving efficiency can be reached when using One Pedal Driving. What strikes however is although all drivers are able to recuperate more energy using OPD, it seems that overall OPD also requires somewhat more positive (traction) energy which means that a somewhat more aggressive driving style is applied while driving with OPD.

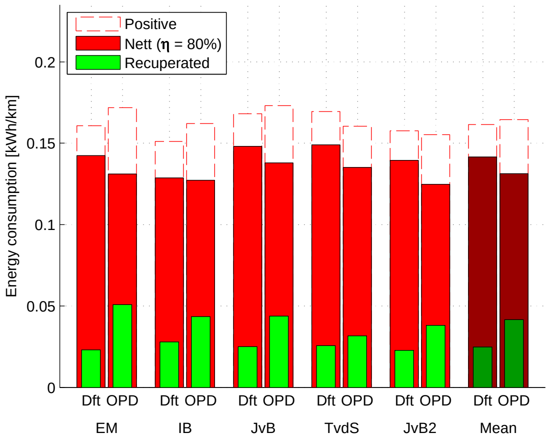

Figure 11: Energy consumption for different drivers in urban driving (default strategy and OPD).

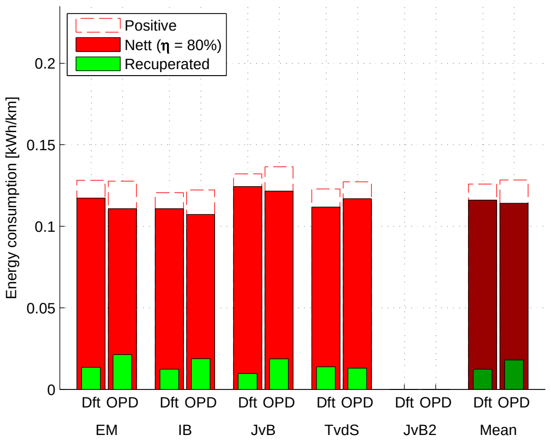

Figure 12: Energy consumption for different drivers driving in rural driving (default strategy and OPD).

The same experiment has been conducted for rural driving, the results are shown in Figure 12. Comparing the energy consumption with urban driving shows that city driving requires on average roughly 17% more energy. What is furthermore noticed is that for this driving condition the mean driving efficiency gain for OPD is only 2%. Driver *'TvdS'* even obtains a worse driving efficiency for OPD primarily caused by the significant lower recuperated energy compared to the other drivers.

To examine the experiments in somewhat more detail, the energy savings for OPD are plotted as a function of the covered distance for drivers *'IB'* and *'JvB'* in Figure 13. Based on this specific experiment, driver 'IB' gains no advantage from OPD after completing the whole city route as was also seen in Figure 11. What strikes is the difference in the evolution of the energy saving during the first 3 kilometers. Whereas for driver 'JvB' the energy efficiency is increased while using OPD, driver 'IB' requires more energy to cover the first part of the route. For the remainder of the route, the energy savings are of the same magnitude, although it seems that the energy savings for driver 'IB' experiences less variation.

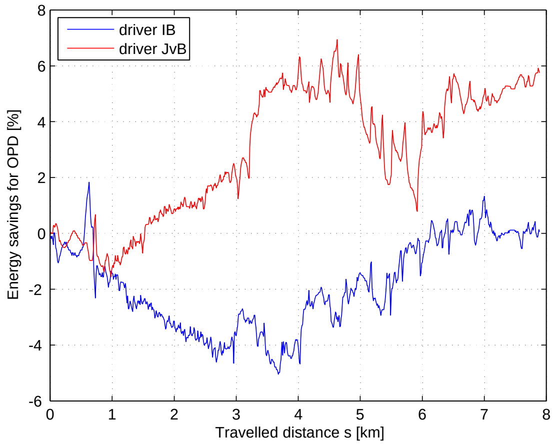

Figure 13: Energy savings for city driving for OPD for drivers 'IB' and 'JvB'.

The preceding findings show that drawing precise conclusions regarding energy savings based on a limited number of real-life measurements is not that straightforward, but the first indications are that OPD results in a reduction of the energy consumption especially for urban driving.

4.2 Pedal operation

Another aspect is the usage of the accelerator and brake pedal by the driver. Figure 14 shows a histogram of the accelerator and Figure 15 the brake pedal position for both the default and OPD algorithm. Some interesting things can be observed. First of all, compared to the default regenerative braking algorithm, applying OPD results in an overall wider spread accelerator pedal position. This is a result of the fact that the accelerator is both used to control deceleration as well as acceleration. What can be noticed furthermore is that while using the default strategy, the accelerator pedal is often fully released.

When considering the brake pedal position one can directly see that during this particular test drive, no situations have occurred where applying the friction brakes was necessary. So full one pedal driving was indeed realized on this occasion.

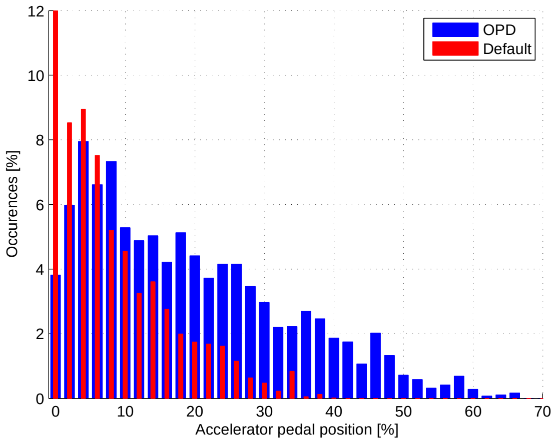

Figure 14: Histogram of the accelerator pedal position for the default regenerative braking strategy and OPD.

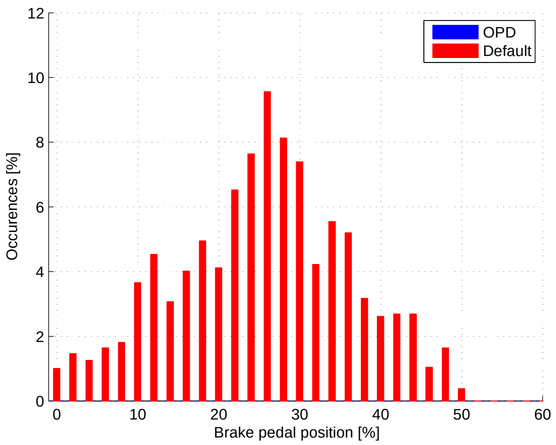

Figure 15: Histogram of the brake pedal position for the default regenerative braking strategy and OPD.

Table 1: Coasting percentages for driving in city and rural traffic.

City		
Driver	***Default***	***OPD***
EM	0.8%	5.8%
IB	0.7%	5.6%
JvB	1.4%	8.9%
TvdS	0.7%	6.2%
JvB2	1.3%	11.2%
Rural		
Driver	***Default***	***OPD***
EM	1.9%	9.2%
IB	1.1%	8.3%
JvB	0.9%	9.1%
TvdS	0.7%	7.8%

Table 1 shows the percentage of total driving time during which the vehicle is coasting, i.e. the drivetrain torque is zero with minimal power requirement. With the default algorithm it is very difficult to coast, as is the case with some production cars discussed in section 2. OPD allows coasting of the vehicle for a considerable amount of time, which is expected to have a positive contribution to reducing the energy consumption.

4.3 Subjective evaluation

Driving tests with various people have shown that switching to One-Pedal-Driving requires only little getting used to. In general, not having to apply the brake pedal is being highly appreciated. Moreover, already after a couple of minutes, drivers feel confident to come to a full stop for traffic lights with a ‘normal’ gap with the vehicle in front.

Most people notice that compared to a conventional vehicle, the pedal has to be pressed further to achieve the required acceleration but did not experience it as being inconvenient. It was however also discovered that this range should not be shifted too much because when overdoing, the vehicle becomes ‘sluggish’ which could result in a less confident driving behavior.

Thanks to the fully customizable acceleration pedal map, the sensitivity of the accelerator pedal can made velocity dependent. Whereas at low velocities a precise torque output can be accomplished to move very smoothly through city traffic, at medium and high velocities the accelerator pedal feels more ‘sporty’ and the vehicle appears to be more powerful.

Drivers furthermore commented positively on the easy way of prescribing the required deceleration while braking and on the amount of deceleration that is available. Also, as was already seen in the preceding section, in general drivers experience no trouble with finding the accelerator pedal position that enables coasting of the vehicle.

5 Conclusions

This paper describes the development and implementation of a One Pedal Driving algorithm. First and for all it must be said that the impact on the drivability of the Lupo EL cannot be underestimated and by far exceeds the initial expectations. Driving tests with a number of different people confirm this positive view, any driver rates OPD higher than the previously used accelerator and regenerative braking strategy map. People can also adapt very quickly to One Pedal Driving and experience it as being very intuitively.

The proposed One Pedal Driving map follows a philosophy very similar to the BMW i3. In real life we are unable to achieve the level of refinement of the BMW i3, as the components used in the Lupo EL less sophisticated. On the other hand, compared to many other electric vehicles on the market today, the proposed algorithm is a clear improvement in our view.

First driving tests seem to indicate that the efficiency of the vehicle has improved slightly, which is to be expected since the friction brakes are not used anymore. A rigorous proof is missing however. Another observation is that seeming unimportant aspects have to be considered. How to switch on the braking lights at the right time? How to handle switching off the cruise control? Should regenerative braking be reduced while cornering?

Future research will focus on analyzing and improving energy efficiency and maintaining vehicle stability for extreme maneuvers and adverse road conditions.

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