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Evaluating the energy efficiency of a one pedal driving algorithm

Jiquan Wang¹, Igo Besselink¹, Joost van Boekel¹, Henk Nijmeijer¹

¹*Dynamics and Control Group, Department of Mechanical Engineering, Eindhoven University of Technology
Den Dolech 2, 5612 AZ Eindhoven, the Netherlands*

Email (corresponding author): j.wang@tue.nl

Abstract

Regenerative braking of electric vehicles (EVs) is important to improve the energy efficiency and increase the vehicle range. However, the additional friction braking during deceleration may limit the amount of recuperated energy. To improve the energy efficiency and driving comfort of EVs, a one pedal driving algorithm (OPD) has been designed. With the OPD algorithm, the vehicle can be driven using accelerator pedal alone in most cases and the brake pedal is only applied in emergency situations. This paper discusses the energy efficiency gains of an OPD algorithm for EVs. The research uses the TU/e Lupo EL, a battery electric vehicle built by Eindhoven University of Technology. Two regenerative braking algorithms are considered: an OPD algorithm and a parallel regenerative braking algorithm (PR). The accelerator maps of the OPD and PR algorithm are introduced and evaluated. The relationship between the vehicle speed and acceleration and accelerator pedal position is more linear for the OPD algorithm compared to the PR algorithm. Subjective tests confirm that the OPD algorithm can provide a much improved driving experience in comparison to the PR algorithm. A coasting area is included in the OPD accelerator map, which is essential for reducing the energy consumption as proved by a MATLAB optimization code. The comparison of energy consumption between the OPD and PR algorithm is analyzed by driving tests and simulations. Measurement results show that over 93% of the regenerative braking energy measured at the high voltage battery terminals can be reused to propel the vehicle. Compared to no regenerative braking, the OPD algorithm can save about 22% energy in city driving and 13% energy in rural driving, while the energy savings are 14% and 9% in city and rural driving respectively for the PR algorithm. Simulation results show that the OPD algorithm can save up to 2% to 9% energy in comparison to the PR algorithm based on the same speed profile for city and rural driving respectively.

Keywords: Electric vehicle, Regenerative braking, One pedal driving, Energy efficiency

1 Introduction

Electric vehicles (EVs) are considered as cars of the future to solve oil dependency and environ-

mental problems. However, the limited driving range is still an obstacle for the adoption of electric vehicles. Regenerative braking is an effective approach for electric vehicles to extend their

driving range [1]. In regenerative mode, the motor acts as a generator, it transfers the kinetic energy to electrical energy, and stores this energy in batteries or capacitors.

In a parallel regenerative braking control strategy, the regenerative braking force is related with the brake pedal travel or brake pressure. Therefore, the regenerative braking is done together with the conventional friction braking. The applied braking force is a combination of the hydraulic braking force and regenerative braking force. Therefore, a part of kinetic energy is still dissipated to heat during braking.

An one pedal driving algorithm (OPD) can be used to improve the energy efficiency. In the OPD algorithm, the accelerator pedal can be used to perform regenerative braking to a certain level, without the need of using the brake pedal and application of the friction brakes. The hydraulic friction brake is only used in emergency cases. One pedal driving is already applied in the BMW i3 and Tesla Model S and is rated quite positively by the drivers [2].

In this paper, the energy efficiency of an OPD algorithm is evaluated. The research is based on the TU/e Lupo EL. The TU/e Lupo EL is built from a donor vehicle, a VW Lupo 3L, by the Dynamics and Control group of Eindhoven University of Technology in 2010. EL is the abbreviation of Electric Lightweight. The TU/e Lupo EL is allowed to drive on the public road since Spring 2011 [3, 4, 5]. Figure 1 gives an impression of the exchange of the driveline, from diesel to battery electric. An important characteristic of the vehicle is the large battery capacity (27 kWh LiFePO₄, 273 kg) in comparison to the vehicle dimensions and mass (1060 kg).

Two regenerative braking control strategies have been implemented in the Lupo EL, a parallel regenerative braking control strategy (PR) [8] and a one pedal driving control strategy (OPD) [2]. The accelerator maps of these two algorithm are analyzed, and the energy efficiency of these two algorithms will be compared based on measurements and simulations. Comparison results show that the efficiency of the OPD algorithm is better compared to the PR algorithm.

This paper is organized as follows. In Section 2, an optimization code is designed to find the optimal speed profile for minimizing energy con-



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

sumption of EVs, which provides a base for the OPD algorithm design. In Section 3 the accelerator maps of the PR algorithm and the OPD algorithm are introduced and analyzed. In Section 4 the battery efficiency is discussed to analyse the amount of regenerative energy that is available for propulsion again. In Section 5 the energy efficiency of the OPD and PR algorithm are verified by driving tests. In Section 6, the energy efficiency of the OPD and PR algorithm are verified by simulation models. Conclusions are given in Section 7.

2 Driving speed optimization

For a given driving distance and time, the driver can choose different driving styles, which lead to different energy consumption results. To obtain the minimized energy consumption, the acceleration profile is optimized to obtain the most efficient driving speed profile, using the MATLAB function FMINCON. The driving scenario is that a vehicle has to arrive at a destination in a fixed time on a straight flat road. There are two driving styles, one is called "constant speed driving", the other one is called "optimal speed driving". For the constant speed driving, the vehicle accelerates to a constant speed, then maintains this speed and finally decelerates to standstill at the destination. For the optimal speed driving, the driving speed is optimized to achieve the minimum energy consumption for the trip.

The simulation is based on an energy consumption model, which can calculate the energy consumption based on driving speed with an error of smaller than 5% for different circumstances [7]. The method to find the optimal driving speed is described in following subsection.

2.1 Optimization problem

The optimization problem is to find the acceleration $a(t)$ over the driving cycle with time length t_d to minimize the cumulative energy consumption with several constraints,

$$E_d = \min_{a(t)} \int_0^{t_d} P(v(t), a(t)) dt \quad (1)$$

subject to $\begin{cases} \vec{h} = 0 \\ \vec{g} \leq 0 \end{cases}$

where E_d is the minimized energy consumption for the trip; t is the time; P is the battery output power, which is determined by the vehicle speed and acceleration [8]; v is the vehicle speed and longitudinal acceleration a is the design variable. The vehicle speed is obtained by the integration of the acceleration,

$$v(t) = v(0) + \int_0^t a(t) dt \quad (2)$$

The equality constraints are: the integration of vehicle speed is equal to the length of the route s_d , the vehicle speed at the start and destination are zero.

$$\vec{h} : \begin{cases} \int_0^{t_d} v(t) dt = s_d \\ v(0) = 0 \\ v(t_d) = 0 \end{cases} \quad (3)$$

The inequality constraints are that the driving speed is within the range of $[0, 120]$ km/h, and the motor power P_m is within the allowed power range of $[-24, 50]$ kW [9].

$$\vec{g} : \begin{cases} 0 \leq v(t) \leq 120 \\ -24 \leq P_m(t) \leq 50 \end{cases} \quad (4)$$

Because there is no traffic flow influence in this driving scenario, the vehicle should be driven as steady as possible to save energy. Therefore, the vehicle is accelerating in the beginning of the trip, and decelerating in the end of the trip, while

in the middle of trip, the driving speed should be almost constant and the acceleration will almost be zero. An example of a longitudinal acceleration profile along the route can be seen in Figure 2. According to measurement (Figure 8), the acceleration upper bound is 4 m/s^2 and lower bound is -2 m/s^2 .

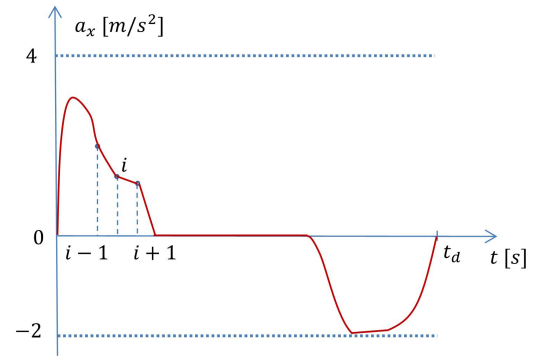


Figure 2: Acceleration profile along a route of the driving scenario.

The vehicle acceleration is dependent on the vehicle motor output power and external resistance forces, thereby, the acceleration profile is not correlated with each other along the driving time. As shown in Figure 2, the acceleration value at $i - 1$ doesn't have any influence on the value at i . For the optimization calculation, if the driving distance and time is short, the acceleration value is set every second. However, if the driving time is too long, for example 10 minutes, 600 values will need to be optimized, resulting in a slow optimization. Thereby, to simplify the calculation for a long time trip, the acceleration is chosen every second one value for the first and last 50 seconds of the trip, while in the middle of the trip, the acceleration time interval is chosen every minute.

2.2 Optimization results

A simulation is done with a distance of 500 meters and a driving time of 40 seconds to compare the energy consumption difference between the constant speed driving and optimal speed driving. The acceleration of constant speed driving and optimal speed driving are shown in Figure 3. The acceleration value is 3 m/s^2 for accelerating and -2 m/s^2 for decelerating in constant speed driving, while in the optimal speed driving, the acceleration is the result of the optimization.

The driving speed and energy consumption results are shown in Figure 4. The optimal speed driving can save 9.7% energy compared to constant speed driving, and the coasting time takes up about 31% of the driving time of the trip.

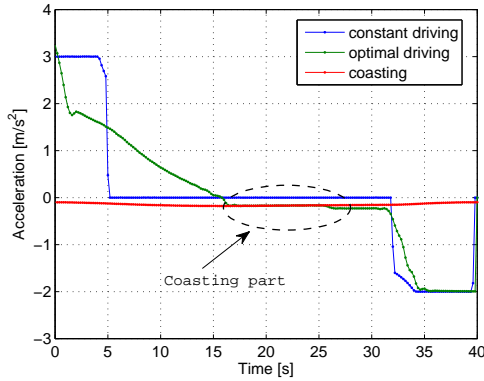


Figure 3: Acceleration for two driving styles.

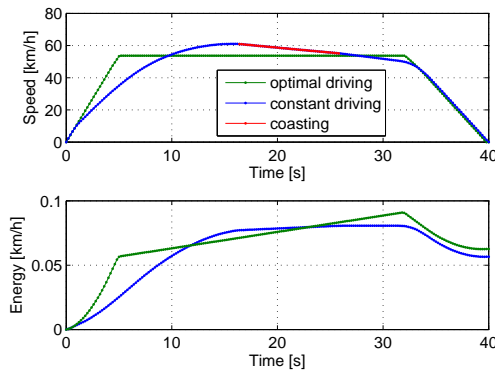


Figure 4: Speed and energy consumption results for two driving styles.

Other simulations with different driving distance and time are also made, including city, rural and highway driving. The details of these simulation scenarios and results are listed in Table 1. It can be seen that the optimal speed driving can save about 10% energy in city driving, but this value will decrease with the increase of driving distance for a rural and highway road. The coasting percentage may reach a value of almost 29% in city driving with the distance of 500 m, and it decreases to 19% in rural road with a distance of 2.0 km. The value will decrease even further to 1.7% in highway road when the total distance is 20 km.

From above analysis, we can conclude that an using optimal speed profile can save energy com-

pared to constant speed driving, and coasting is essential for reducing the energy consumption. Therefore, to save energy, the control strategy of the vehicle accelerator pedal should be designed to make the driver to coast easily.

Table 1: Comparison between the constant speed driving and optimal speed driving

	s [km]	t_d [s]	v_m [km/h]	E_c [Wh]	optimal		ΔE [%]
					E_{op} [Wh]	C_p [%]	
C	0.1	14	25	19	17	10.0	10.7
	0.2	21	34	30	27	12.4	11.0
	0.3	31	35	39	34	19.4	12.4
	0.5	50	36	54	48	28.8	11.6
R	1.0	69	52	110	101	22.6	8.2
	1.5	103	52	151	141	20.0	6.4
	2.0	130	55	198	188	18.5	4.9
H	5.0	185	97	698	683	5.8	2.2
	10.0	359	100	1349	1333	3.3	1.2
	20.0	712	101	2626	2608	1.7	0.7

Note: C is city road; R is rural road; H is highway; s is driving distance; t_d is driving time; v_m is the average driving speed; E_c is the energy consumption of constant speed driving; E_{op} is the energy consumption of optimal driving; C_p is the percentage of coasting in optimal speed driving; ΔE is the energy saving of optimal driving compared to constant speed driving.

3 EV accelerator pedal maps

The regenerative braking control strategies are illustrated by accelerator pedal maps, which show the vehicle longitudinal acceleration a_x at a specific forward speed and accelerator pedal position. When a_x is positive, the vehicle is accelerating; when it is negative, the vehicle is decelerating.

3.1 PR control strategy

In the parallel regenerative braking control strategy of Lupo EL, the regenerative braking force is a function of the brake pedal travel. The vehicle total braking force is a combination of hydraulic and regenerative braking force. For a specific driving speed, the hydraulic and regenerative braking force are increasing with the brake pedal travel. The relationship between the vehicle total braking force and regenerative braking force with brake pedal travel are shown in Figure 5 for a driving speed of 60 km/h. It can be seen that when the brake pedal travel is below 10%, the hydraulic braking force is zero, this is the free travel between the brake disc and brake pads. When the brake pedal travel is bigger than

60%, the regenerative braking force is reduced to zero, which is to ensure the braking stability in an emergency case. For more details see reference [6, 8]. The accelerator map of the PR control strategy is shown in Figure 6.

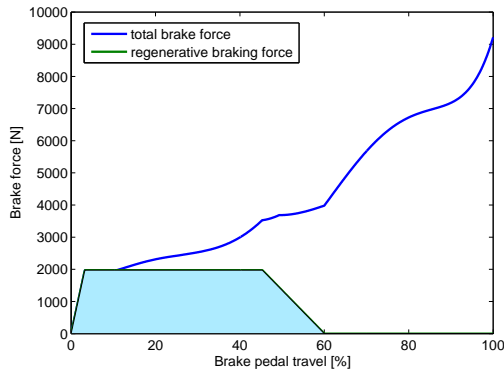


Figure 5: Braking force relationship in the PR algorithm at 60 km/h.

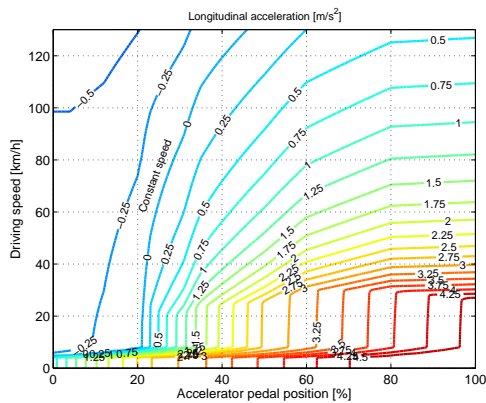


Figure 6: PR accelerator pedal map.

The PR control strategy has two disadvantages. The first issue is that the constant speed and acceleration lines are not linear with the accelerator pedal travel, which may not provide a comfortable and consistent behavior for the driver. The second issue is that the hydraulic braking system is nearly always working during braking, which results in part of the energy being transferred into heat.

3.2 OPD control strategy

3.2.1 General requirements

After analyzing the limitations of the PR control strategy in the Lupo EL, an OPD control strat-

egy is designed to improve the energy efficiency and driving feeling. The OPD algorithm has been designed to fulfill several requirements listed below. For more details on the OPD algorithm, see reference [2].

1. The driver should be able to control the acceleration and deceleration by the accelerator pedal only for normal driving conditions. The vehicle can come to a full stop without using the brake pedal.
2. The driver is able to freely select the desired deceleration level with the accelerator pedal not being overly sensitive.
3. The brake pedal is only used in emergency cases. For these rare conditions energy harvesting is considered not important and the friction brakes are used to achieve the desired deceleration.
4. There is no change in deceleration when releasing the accelerator and applying the brake pedal.
5. A coasting mode with minimal energy usage can be selected by the driver.
6. When cornering at high lateral acceleration the level of regenerative braking will be reduced to ensure vehicle stability.

3.2.2 OPD accelerator pedal map

The accelerator map of the OPD algorithm is shown in Figure 7. It can be seen that the relationship between accelerator pedal position and constant velocity driving ($a_x = 0$) is almost linear. Also a coasting range exists in the accelerator map. In this region the vehicle is neither propelled nor braked electrically, indicated with the green area in Figure 7. The benefit of coasting is verified in Section 2.

The relationship between the acceleration and speed in a driving test on a public road is shown in Figure 8 [7]. It can be seen that the maximum acceleration is almost the same as the PR algorithm, while regenerative braking can achieve a maximum deceleration of approximately 2 m/s^2 at a forward speed below 40 km/h.

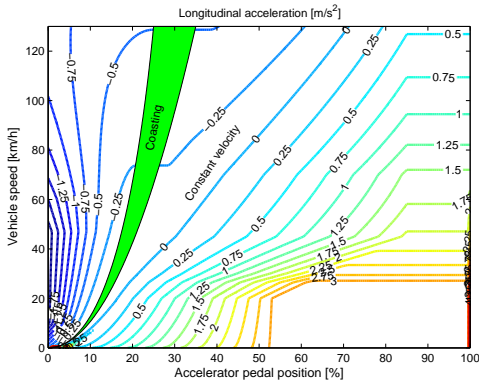


Figure 7: OPD accelerator pedal map.

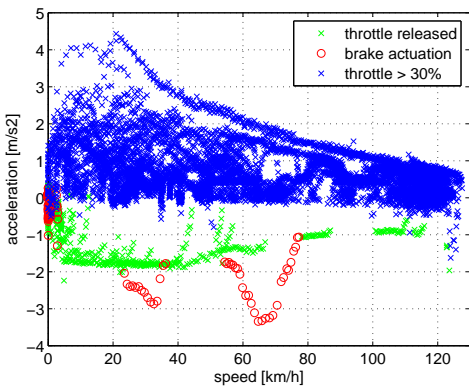


Figure 8: A driving test of the OPD algorithm.

4 Battery efficiency

The energy originating from regenerative braking is stored in the battery and extracted at a later stage for propelling the vehicle, this process has some inherent energy losses that will be analyzed in this section. The battery efficiency is analyzed by driving tests on public road. Four driving tests have been done in October 2015, including city and rural driving. The driving distance and energy consumption measurements are listed in Table 2. It can be seen that the regenerative energy E_{reg} is almost zero in test 2 and test 4, because regenerative braking was disabled, while the regenerative braking is active in test 1 and test 3. To simplify the calculation, the battery charging efficiency from the power socket and from regenerative braking are assumed to be the same. The charging efficiency and discharging efficiency are combined together as the overall battery efficiency. Thereby, the energy discharged from the battery should be equal to the energy charged into

the battery multiplied by the battery efficiency η_{bat} ,

$$(E_{dc} + E_{reg}) \cdot \eta_{bat} = E_{dis} \quad (5)$$

where E_{dc} is the battery charging energy from power socket; E_{reg} is the energy from regenerative braking and E_{dis} is the battery discharging energy.

The battery efficiency can be calculated based on Equation 5, the results are listed in Table 2. The mean efficiency of the battery among four tests is 93.2%. Therefore, more than 93% of the regenerative energy measured at the high voltage battery terminal can be extracted again and used for propulsion. This value will be used to analyze the energy consumption of electric vehicle in measurements and simulations in Section 5 and 6 respectively.

Table 2: Energy and battery efficiency on rural and city road tests

		rural road		city road	
		Test 1 regen	Test 2 no regen	Test 3 regen	Test 4 no regen
drive	s	101.2	99.0	67.2	66.9
	E_{reg}	2.72	0.03	4.85	0.00
charge	E_{dis}	14.75	13.80	13.86	11.04
	E_{ac}	14.95	16.87	11.87	13.69
result	E_{dc}	12.90	14.55	10.27	11.74
	η_{bat}	93.7	94.7	90.3	93.9

note: s is the driving distance [km]; E_{reg} is the regenerative braking energy during driving [kWh]; E_{dis} is the discharging energy during driving [kWh]; E_{ac} is the charging energy from power socket [kWh]; E_{dc} is the charging energy into battery [kWh]; η_{bat} is the battery efficiency [%].

5 Measurement verification

The performance of the OPD and PR algorithms are evaluated by driving tests on the public road in 2014. Because the vehicle driving speed on highway road is almost constant, the regenerative braking energy is limited. Therefore, the driving route in this verification only includes a city route and a rural route. The length of the city driving is 7.9 km and 18 km for rural driving. The vehicle is driven on the same route twice by one driver, with OPD algorithm and PR algorithm respectively. In total four drivers are involved in this test. The city driving route and rural driving route are shown in Figure 9 and Figure 10 respectively.

The total energy consumed from the battery



Figure 9: City route in Eindhoven centre.

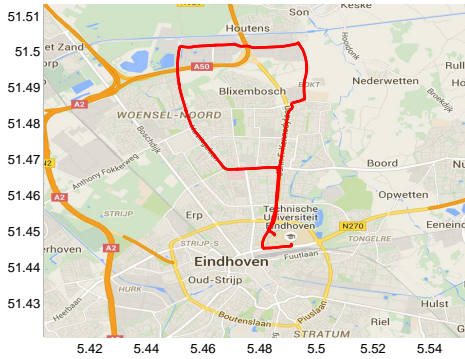


Figure 10: Rural route in Eindhoven area.

E_{total} can be calculated as

$$E_{total} = E_{dis} - E_{reg} \cdot \eta_{bat} \quad (6)$$

where E_{dis} is the discharged energy from battery; E_{reg} is the regenerative braking energy and η_{bat} is the battery efficiency.

The energy savings of the OPD algorithm ΔE compared to the PR algorithm can be calculated as

$$\Delta E = (E_{PR} - E_{OPD})/E_{PR} \cdot 100\% \quad (7)$$

where E_{PR} is the energy consumption measured using the PR algorithm and E_{OPD} is the energy consumption measured using the OPD algorithm. The test dates and energy consumption results in city route and rural route for four drivers are listed in Table 3. It can be seen that the OPD algorithm saves energy in most trips. However, due to the influence of traffic flow, the driving speed profile is not the same on the same route in different tests, even for the one driver. Therefore,

the measured energy consumption is not only determined by the regenerative braking strategy.

Table 3: Total energy consumption in city and rural test

driver	date	city route			rural route		
		PR	OPD	ΔE [%]	PR	OPD	ΔE [%]
EM	Nov. 20	1.13	1.02	9.7	2.09	1.95	6.7
IB	Nov. 25	1.00	0.99	1.1	1.97	1.90	3.6
JvB	Dec. 02	1.16	1.07	7.8	2.22	2.15	3.2
TvdS	Dec. 03	1.17	1.06	9.4	1.99	2.07	-4.0

Note: the unit of energy is [kWh]; ΔE is the OPD energy saving to the PR algorithm.

5.1 Coasting percentage

The coasting percentage results of the 16 tests are listed in Table 4. It can be seen that the mean percentage of coasting for the OPD algorithm is about 6.6% in the city route and 8.6% in the rural route, compared to 0.9% in the city route and 1.2% in the rural route for the PR algorithm. This demonstrates that the driver can coast more easily with the OPD algorithm than PR algorithm in both city and rural driving, which may contribute to a lower energy consumption.

Table 4: Percentage of coasting in city and rural tests

driver	date	city route		rural route	
		PR	OPD	PR	OPD
EM	20141120	0.8	5.8	1.9	9.2
IB	20141125	0.7	5.6	1.1	8.3
JvB	20141202	1.4	8.9	0.9	9.1
TvdS	20141203	0.7	6.2	0.7	7.8

Note: the unit is [%]

5.2 Energy efficiency

To offer a better impression on the energy efficiency differences of these two strategies, the discharged energy, regenerative braking energy and total energy consumption per kilometer are calculated and the results are shown in Figure 11 and 12. It can be seen that the energy consumption per kilometer for city driving is higher than on the rural road. All drivers can recuperate more energy using the OPD algorithm. However, it appears that the trip with OPD algorithm also requires more discharge energy, which means that a somewhat more aggressive driving style is applied when driving with the OPD algorithm. The energy saved by the regenerative braking can be

calculated by comparing the difference between the total energy consumption and the discharged energy value. According to the calculation, the regenerative braking can save about 22% energy in city driving and 13% energy in rural driving for the OPD algorithm, compared to 14% and 9% in city and rural driving respectively for the PR algorithm.

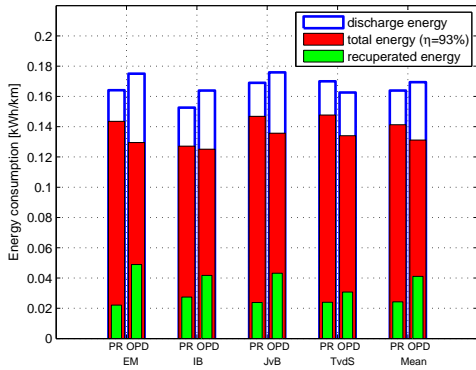


Figure 11: Energy consumption per kilometer for different drivers in city road.

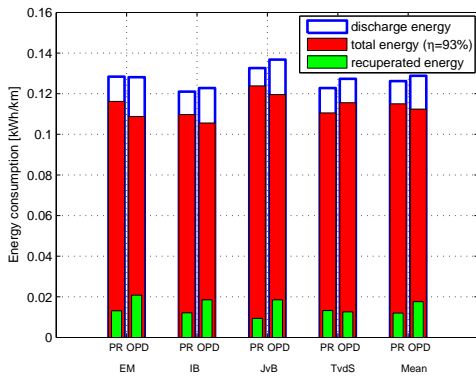


Figure 12: Energy consumption per kilometer for different drivers in rural road.

The energy savings for the OPD algorithm by four drivers in the city route and rural route are shown in Figure 13 and Figure 14. It shows that the OPD algorithm leads to energy savings in most cases. However, due to the influence of traffic flow, there are some negative results.

To remove the influence of traffic flow, the battery output power at a specific speed and acceleration is calculated based on the measurement of 16 tests. The relationship between the battery output power and acceleration at a specific driv-

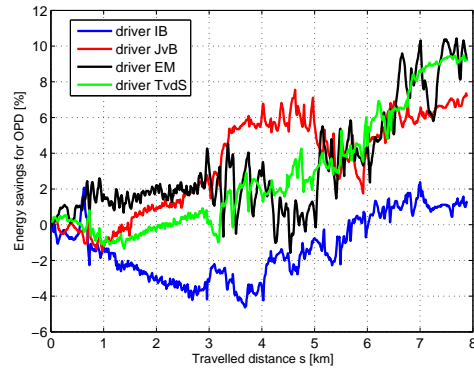


Figure 13: Energy saving for the OPD algorithm in city driving.

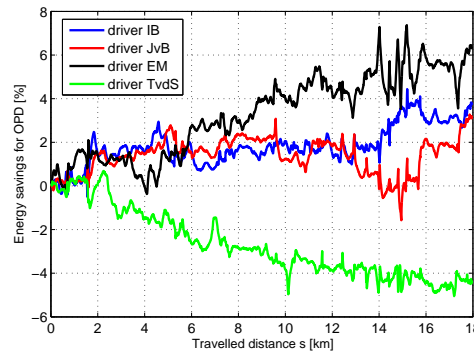


Figure 14: Energy saving for the OPD algorithm in rural driving.

ing speed can be calculated. Then the power efficiency of these two algorithm can be compared. The relationship between the battery output power and the acceleration of these two algorithm at 25 km/h is shown in Figure 15 as an example. It can be seen that the battery output power is almost the same for these two algorithm in traction mode, but for regenerative braking, the recuperated power of the OPD algorithm is higher than the PR algorithm, which explains the higher energy efficiency seen with the OPD algorithm.

6 Simulation

The improved efficiency of the OPD algorithm can also be verified by simulations. Two energy consumption models, the PR model and OPD model, are used to calculate the energy consumption based on the measured driving speed profile. These two models are built based on the

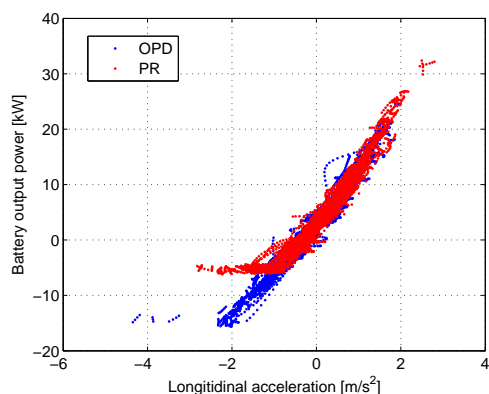


Figure 15: Battery output power of the OPD and PR algorithm at 25 km/h.

PR algorithm and OPD algorithm respectively, and can estimate the energy consumption with an error of smaller than 5% under different circumstance [7]. As mentioned in Section 5, four drivers are involved in this verification, and for each driver four measured speed profiles exist. For every measured speed profile, the PR simulation model and OPD simulation model are used to calculate the energy consumption respectively, and then the energy difference is calculated.

The energy saving for the OPD algorithm compared to the PR algorithm for each test is shown in Table 5. The mean energy saving is 6.0% in the city test and 2.2% in the rural test. These results confirm that the OPD algorithm can save more energy than the PR algorithm with the same driving speed, and the advantage is bigger for city driving compared to rural driving. The comparison results of two algorithms in a city route and rural route are shown in Figure 16 and 17 respectively.

Table 5: Percentage of energy saving of the OPD algorithm in simulation. PR and OPD refers to the speed profile measured during the tests

driver	date	city route		rural route	
		PR	OPD	PR	OPD
EM	20141120	6.5	8.5	2.4	3.3
IB	20141125	5.3	6.6	2.1	2.2
JvB	20141202	6.5	7.2	3.2	2.8
TvdS	20141203	3.2	4.1	0.6	1.4

Note: the unit is [%]

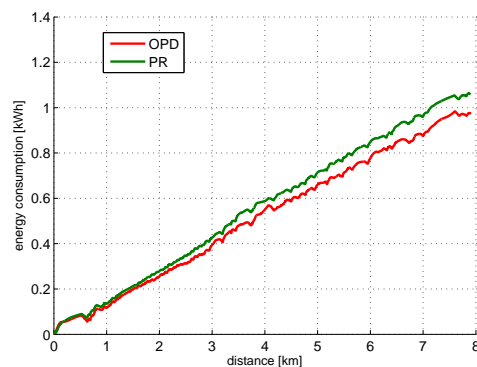


Figure 16: Energy consumption in city driving.

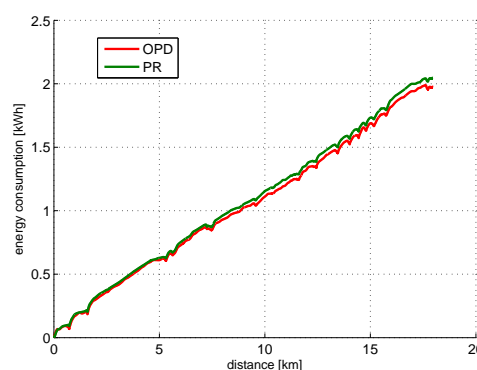


Figure 17: Energy consumption in rural driving.

7 Conclusions

The purpose of this paper is to evaluate the energy efficiency of an OPD algorithm. For the OPD algorithm, the vehicle can be driven only by the accelerator pedal in most cases and the brake pedal is only used for emergency cases.

In this paper, the effect of an OPD algorithm is elevated through measurements and simulations. A comparison of the accelerator map of the OPD algorithm and the PR algorithm suggests that constant speed driving and acceleration is almost linear with the accelerator pedal travel, which subjectively provides a more comfortable driving experience. A coasting area has been introduced in the OPD accelerator map, the benefit of coasting is shown by optimizing the energy consumption for a given trajectory.

The energy efficiency of the OPD algorithm is verified by driving tests on public road and simulations. The comparison demonstrates that the battery output power of the OPD algorithm and the PR algorithm are almost the same for trac-

tion, but the OPD algorithm can recuperate more energy during braking. Measurements show that more than 93% of the regenerative energy measured at battery output can be used again for propulsion. The simulation result suggests that the OPD algorithm can save up to 2% to 9% energy compared to the PR algorithm based on the same driving speed in city and rural driving.

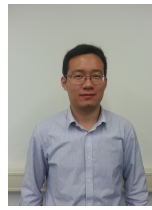
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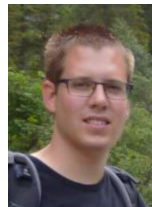
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Authors



Jiquan Wang is a PhD at the Eindhoven University of Technology, Department of Mechanical engineering, Dynamics and Control. Current research activities include electric vehicle energy modelling and driver support building.



Joost van Boekel is a master student at the Eindhoven University of Technology. His main interests are vehicle dynamics, regenerative braking, accelerator response and electric vehicles innovations in general.



Dr. Ir. Igo Besselink is an assistant professor at the Eindhoven University of Technology, department of Mechanical engineering, Dynamics and Control. Research activities include tyre modelling, vehicle dynamics and electric vehicles.



Prof. Dr. Henk Nijmeijer is a full professor at the Eindhoven University of Technology, department of Mechanical engineering, Dynamics and Control. Current research activities include non-linear dynamics and control.