OPTIMIZATION OF BRAKING ENERGY RECUPERATION BY USING DRIVER DATA STATISTICS

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ABSTRACT: Fuel efficiency hybrid vehicles and full electric vehicles are using braking energy recuperation technology to increase the autonomy as much as possible. Efficiency of braking energy recuperation can be highly dependent on the driving stile, vehicle speed during braking manouvers or level deceleration requested by the driver. This paper propose an analysis to detect the optimum range for braking energy recuperation based on classification of the type of braking events, vehicle speed and deceleration. To reach this goal a long-term capture data collection from a fleet of vehicles driven in normal everyday use, is used as input for this study. The results of the statistical analysis performed, reveal important new data on braking events patterns which contributes to the development of hybrid braking systems by covering the lack of data available regarding braking maneuvers of real life vehicle exploitation.

KEY WORDS: Regenerative Braking, Hybrid Electric Vehicle, Kinetic energy recuperation

1 INTRODUCTION

Alternative drive technologies are becoming more present in automotive industry in the context of finite fossil fuels worldwide, therefore important efforts concentrate to electrify the vehicles power-train.

The future of electrical power-train is greatly dependent on their range and battery storage capacity. To increase the autonomy of hybrid and electric vehicles recovery of the braking energy has been a subject of development in many development research centers in different automotive suppliers and OEM's.

In conventional type of braking system, the kinetic energy is converted into hit through friction in order to produce deceleration. Hybrid and electric vehicles are equipped with generators to recover some of the kinetic energy and store it as electrical energy in an on board battery. The questions which arrays are "**How effective are regenerative braking systems**?" and "**How can be improved**?"

The work in this paper for answering those questions starts from analyzing the basic principle of the existing technology. The electrical motors are used as generators to decrease the vehicle velocity when this is requested by the driver.

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In many situations the generators "braking power" is enough reduce the vehicle speed. When more braking torque is necessary then the generator alone can provide, additional braking force is added by the conventional friction brakes.

The key point of regenerative braking systems is the interaction between friction brakes and generator to maximize the efficiency on energy recuperation. In Fig.1, the deceleration level which can be produced with different types of generators is presented in relation with vehicle speed. At low speeds maximum brake torque is available. At high speed or very low speed sufficient brake torque cannot be provided which means that friction brakes must be activated.

By braking with conventional friction brakes a part of the kinetic energy which could be recuperated is lost converted into hit and dissipated into environment.

To increase the energy recuperation, generators should be used for as many brakes apply as possible. Taking in the consideration the limitations in braking torque that generators can provide and the unknown brake torque request by the driver in a normal real life braking situation, this paper propose a statistical analysis study for the total brake applies in a vehicle lifetime.

The goal is to identify the range where most of the braking events take place in terms of:

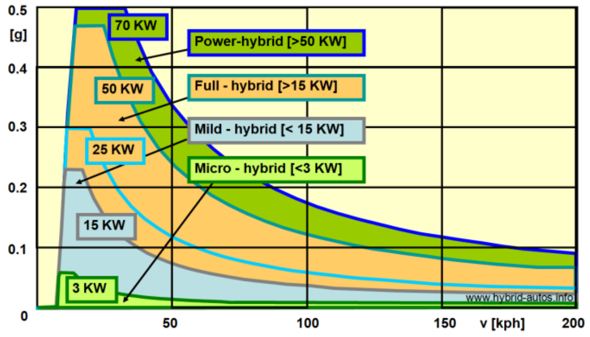

Figure 1. Deceleration characteristics for different generators

At what vehicle speed does the braking event starts ?

At what vehicle speed does the braking event end

What level of deceleration is the most required and for what range of vehicle velocity?

and detect the optimum range for braking energy recuperation based on classification of the type of braking events, vehicle speed and deceleration.

2 DATA USED IN THE ANALYSIS

For this study a fleet of five different vehicles have been chosen. The vehicles are typical passenger cars of different engine capacity driven in the area of Frankfurt, Germany. Table1 shows a short overview over the real-time collected data and highlights important information like the number of observation days, kilometres travelled by the vehicles and characteristics regarding vehicle engine type and power.

Equipment records the vehicles movements between each ignition on and ignition off called one “driving event”. Recording is done at a rate of every 100[ms] manning that ten times per second for each signal, one measured value is registered. The data collected is transferred on a PC where is analyzed using custom software developed using MATLAB.

Table 1 Data overview

OEM	Model	Obs. in [days]	Traveled distance [km]	Engine Type
Daimler AG	C320	821	71,308	Otto
Daimler AG	C200	618	38,980	Otto
Daimler AG	C320	798	54,257	Diesel
Daimler AG	C220	245	28,711	Diesel
Daimler AG	C220	449	51,783	Diesel
Daimler AG	C320	186	13,494	Otto

A sample of drive recorder data is presented in figure 2, where tree signals are represented:

- vehicle velocity [km/h]
- lateral acceleration[m/s^2]
- longitudinal acceleration [m/s^2]

This particular recording represents one driving event which has a length of 300[s]. One recording is starting each time vehicle ignition is on and last until the driver switches off the vehicle ignition.

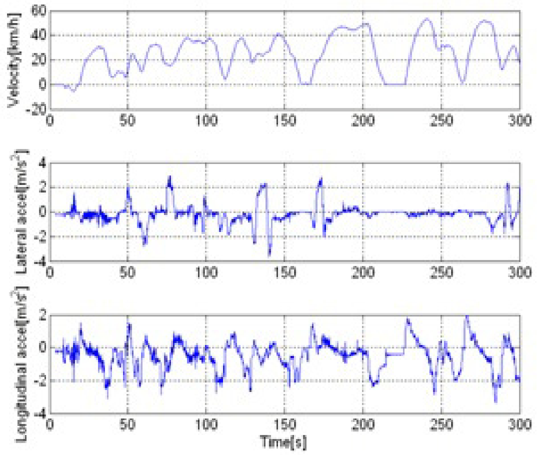

Figure 2 Recording sample for velocity and acceleration

3 BRAKIING MANOUVERS ANALYSIS

3.1 General classifications and analysis

In this subsection a general analysis over the vehicle braking system is performed. Results of this section correspond to the analysis of the entire collection of data and statistically are presented in table 2.

From this overview it appears that from the total vehicle exploitation time 16.6 % is covered only by braking. Analysis shows a number of 108 brakes applied for each hour of driving and 1.8 brake events for each travelled kilometre.

Table 2 Braking maneuvers overview analysis

Data	Value	Unit
Total recording time	2998:02:50	hh:mm:ss
Total distance travelled	180.244	[km]
Braking events number	324.160	event number
Braking events number per kilometre	1,8	event / km
Braking events number per hour	108,12	event / h
Total braking time	501:26:19	hh:mm:ss

In the next step analysis, braking manoeuvres are classified into five different categories. The definition of each category depends on the state of motion of the vehicle when brake pedal is applied and when the pedal is released.

driving: Vehicle is moving continuously during the braking time and it counts the brake pedal until its release;

stopping: The vehicle is in motion when the brake is applied and vehicle reaches zero velocity when brake pedal is released;

stand-still: vehicle is continuously standing still during total brake apply from the moment when brake is applied until the moment the brake is released;

stop & go: vehicle is driving, comes to stand still, reaccelerates again and brake is released when vehicle is moving already (typically for automatic transmissions);

drive off: vehicle is standing still at brake apply and brake is released when vehicle is moving already (typically for automatic transmissions);

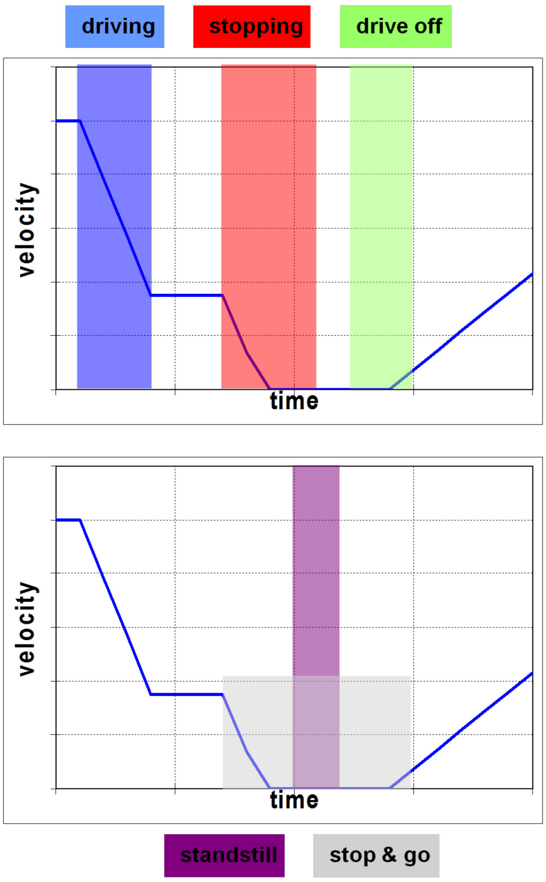

Figure 3 Brake events defined categories

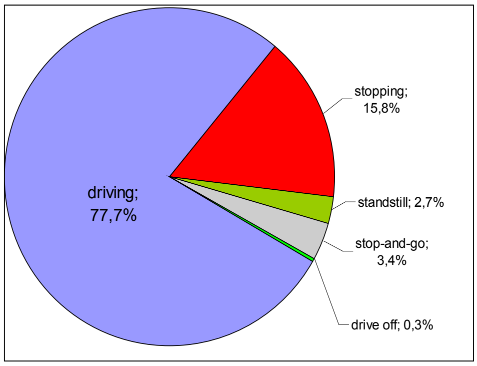

Figure 4 Brake applies classification based on the braking categories

Using the braking classification described above the result of the analysis indicates (figure 4) that from the total number of brake events 77% of them are part of the first category called "driving" where the initial and final velocity is above zero.

The next category "stopping" summarize 15.8% out of all braking situations and 2.7% for the "standing still" situation where brake is applied during vehicle zero velocity (typically for waiting at a traffic light).

The next two categories stop & go and drive off are brake events at very low velocities up to 5/kph and are mainly caused by driving in busy traffic situations.

The importance of having a classification of this type is useful in order to divide results based on the brake applies category.

3.2 Detailed analysis of braking maneuvers

In order to obtain a more detailed analysis, in this section are used 3D histograms. These type histograms consist in data correlated for tree signals in such a way that each brake event can be better evaluated.

For this reason several types of histograms have been developed which correlate vehicle velocity, duration of braking manoeuvre and deceleration level during braking which has a major contribution in detecting the area where efficiency of energy recuperation is highest.

3.2.1 Initial and final velocity for all brake events

In figure 5 is presented a classification of the number of brake events applied during vehicles operation (in colour scale) where initial velocity is classified on the y-axis and final velocity on the x-axis.

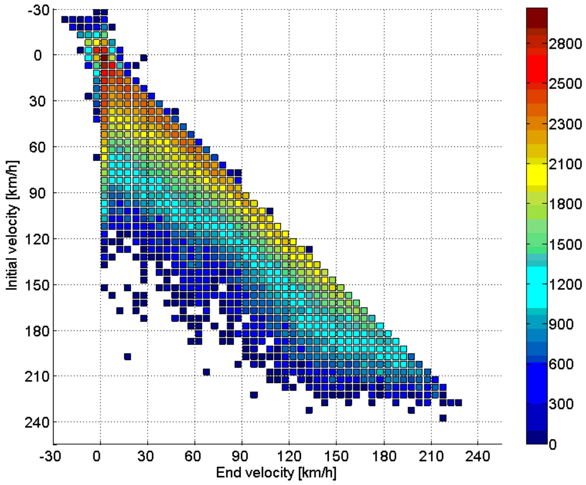

Figure 5 Number of brake events vs. initial and final vehicle velocity.

Table 3 Braking maneuvers classification by velocity categories

Type of brake apply	initial velocity [km/h]	final velocity [km/h]	brake number	Number of brakes in percentage [%]	duration [s]	duration percentage [%]
total	all	all	248971	100%	1394650.1	100%
stopping	<10	[0 5)	4965	2%	4282.9	0.31%
stopping	>5	[0 5)	17563	7.05%	40981.4	2.94%
driving	>20	>5	141436	56.81%	323320	23.18%
driving	>20	>10	135422	54.39%	295980.3	21.22%
driving	>20	>20	118271	47.50%	242684.4	17.40%
driving	>30	>30	99334	39.90%	201948.1	14.48%
driving	>60	>30	66602	26.75%	168345.3	12.07%
driving	>60	>40	63432	25.48%	157076.7	11.26%

The difference between the vehicle initial velocity and final velocity for in most of the brake applies is in average of around 20km/h and represents a high number of brake applies.

There are also brakes events which can be defined as emergency brakes where initial vehicle velocity is above 100km/h and end velocity is zero. In table 3 several categories have been defined for the braking conditions.

The interest of the observation is to detect the range of velocities where most of the brakes are applied; each category definition depends on the vehicle state of motion and initial and final velocity. Values presented in the analysis table are:

- Number of brake applies for each category defined and their corresponding ratio in percentage from the total number of braking manoeuvres.
- The duration – time measured in seconds for each category defined and the corresponding percentage ratio from the total time of braking.

The results of this analysis indicates that the highest category of brakes apply represents 56% from the total barking manoeuvres where initial velocity is higher than 20Km/h and final velocity higher than 5km/h.

This represents the range for witch kinetic energy recuperation can be performed using generators and consists in 90 hours of braking and 141436 thousands of brake manoeuvres.

3.2.2 Number of brake events initial velocity and average deceleration;

Figure 6 represents the classification created in order to bring more information regarding vehicle deceleration during each braking maneuver.

Therefore, initial velocity of the each brake event is classified on the y-axis and on the x-axis the corresponding average deceleration during braking. Table 4 presents all break events classified in five categories depending on the deceleration values.

The categories are defined with a step of 0.1g and the table applied corresponding to each category as well as the percentage.

From this histogram can observe that most of the brakes manoufers are in a range of average deceleration of 0.1 - 0.2g and present on the range velocity from 0 – 120km/h. If braking is done using the generators kinetic energy can be recuperated.

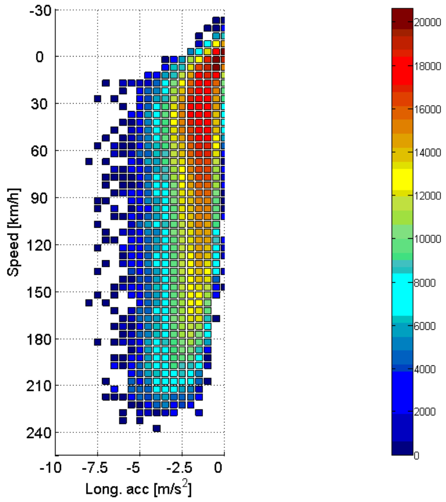

Figure 6 Classification of brake events initial velocity and average deceleration level.

On the other hand, brakes applies which exceed 0.3g are representing only 3.2% from the total number of brake events and they are present on the entire range of vehicle velocities.

These brake events represent a low percentage from the total, therefore kinetic energy recuperation for these events make no sense.

Table 4 Classification by level of deceleration

Deceleration level category	Brake number	Brake number [%]
brakes 0 - 0.1g	73779	29.63%
brakes > 0.1 - 0.2g	123646	49.66%
brakes > 0.2 - 0.3g	42487	17.07%
brakes > 0.3 - 0.4g	6473	2.60%
brakes > 0.4g	1526	0.61%

3.2.3 Number of stops and deceleration distribution

The following histogram of the analysis in figure 7 represents the deceleration distribution correlated with initial velocity only for the brake applies where final velocity is zero.

This histogram helps to visualize how deceleration is distributed during brake events where final vehicle velocity is zero ("stopping").

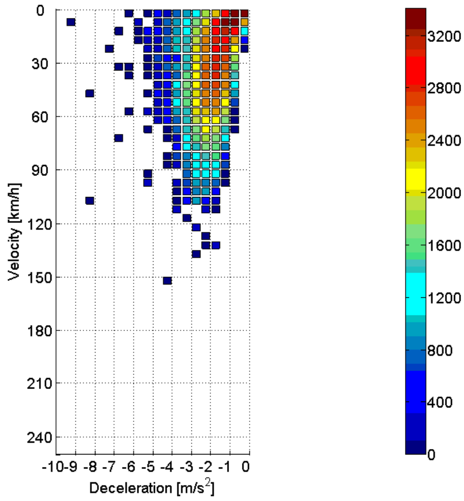

Figure 7 Classification of brake events with final vehicle velocity zero

Table 5 shows that a brake event where deceleration level is higher than 0.4g are rare and represents 0.27% from the total number of stops, and in addition corresponding time duration for these stops is 0.18%.

Table 5 Classification by level of deceleration

Deceleration level category	Brake number	Brake number [%]
Total	45197	100%
brakes 0 - 0.1g	16302	36.07%
brakes > 0.1 - 0.2g	20026	44.31%
brakes > 0.2 - 0.3g	7283	16.11%
brakes > 0.3 - 0.4g	910	2.01%
brakes > 0.4g	123	0.27%
Deceleration level category	**Brake time duration[s]**	**Duration in percentage [%]**
Total	215331	100%
brakes 0 - 0.1g	51605	23.97%
brakes > 0.1 - 0.2g	113192	52.57%
brakes > 0.2 - 0.3g	7283	3.38%
brakes > 0.3 - 0.4g	4473	2.08%
brakes > 0.4g	381	0.18%

Number of stops means that for each brake apply form the above table end velocity of vehicle is zero, this means that for the last part of braking from 10[km/h] up to vehicle stand still the generator will not be able to produce any deceleration and all braking torque in this range will have to be done by the friction brakes.

The total number of stops represents 15.8% from the total number of brake applies and for all this events a switch between conventional friction brakes and generator must be performed.

4 CONCLUDING REMARKS

A general overview and a detailed analysis regarding brake events during vehicles exploitation in real-life has been presented.

The motivation of this research was to cover the lack of information available to describe the driver behaiviour in real life and the braking manouvers pattern in a sufficient way.

This study contributes to the reserch of vehicle brake kinetic energy recuperation in automotive industry in order to answer questions where before was difficult to answer or answered ware made mainly based on based estimations.

From the results of this analysis it is shown that the range of interest for the braking energy recuperation has been identified based on data statistics with an important level of accuracy.

Both tables 3, 4 and 5 reveal important data regarding brake applies in terms of deceleration distribution over the velocity interval, number of brakes and their duration, percentage ratio for different proposed classifications.

In the conclusion of this paper in figure 8, it is pointed out the area for the most efficient interval for energy recuperation which is for velocities under 80km/h and a deceleration level up to 0.2g which cover 80% from the total brake events during vehicle life.

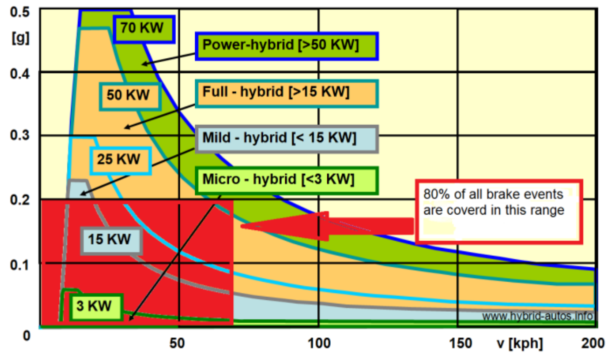

Figure 8 Optimum velocity range and deceleration level for kinetic energy recuperation

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