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TECHNICAL PAPER

A novel method for the design of regenerative brake system in an urban automotive

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Abstract Environmental problems a nd fossil fuel limitations have made the automobile manufactures use renewable energies and energy recovery systems; therefore, particular attention has been paid to hybrid vehicles and/or biofuel vehicles. In this paper, the main objective is to study the appropriate strategy for choosing a better alternative to fossil fuels. Here, one of the strategies is using some devices in order to reduce the waste energies and the other is providing the condition in order to reuse the energies. For this purpose, the regenerative braking system could be mentioned as an energy recovery mechanism which slows a vehicle down by converting its energy into another form, which can be either used immediately or stored until needed. In this work, the design of regenerative braking system in hybrid vehicles has been considered and conducting a few tests, based on ISO 6469 standards; recycled energy at different speeds has been investigated. Also comparison of brake distance of this vehicle in two conditions, with and without regenerative braking has been made. The results show that this system is suitable in high speeds, but in low speeds conventional braking system has better efficiency.

Keywords Regenerative braking · Hybrid vehicles · Waste energy · Braking distance

Abbreviations

APU	Auxiliary power unit
ABS	Anti-lock braking system
Rb	Regenerative braking

List of symbols

$\mathbf{X}$	Parameter vector
X	Parameter scaler
F	Force (N)
C	Pedal ratio (%)
M	Vehicle mass (kg)
A	Area (m^2)
P	Load (N)
C_D	Aerodynamic drag coefficient (%)
δ	Rotational inertia factor (%)
dV/dt	Vehicle acceleration (m/s^{2})
$\boldsymbol{e}_{fL}$	Unit direction vector of the load received from the left flank of the pinion tooth
K	Motor constant
ω	Rotor speed (rad/s)
P_d	The generated power using regenerative brake (kW)
P	Motor power (kW)
β_p, β_r	Angle in Fig. 3
t_R	Reaction time (s)
t_b	Braking time (s)
ω	Pinion angular velocity
u	The rack movement velocity to the axial direction (m/s)

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r	Pitch circle radius of the pinion (m)
$\sum$	Angle between axes on rack and pinion
β	Ratio P to P_d (%)
R	Ratio $X_{R,regenarative}$ to $X_{R,convetional}$(%)
R_a	Resistance (Ω)
μ_2	Rack guide friction coefficient in rack axial direction. (%)

Subscripts

t_r	Time interval for the vehicle using regenerative brake(s)
V	Vehicle speed (m/s)
X	Displacement (m)
g	Gravitational acceleration (9.81 m/s^2)
ρ_a	Air mass density (1.205 kg/m^3)
f_r	Tire rolling resistance coefficient (%)
μ_1	Tooth flank friction coefficient (%)
$\boldsymbol{e}_{fR}$	Unit direction vector of the load received from the right flank of the pinion tooth
W	Rack guide load (N)
I_a	Armature current (A)
E	Induced voltage
T	Torque (N m)
f	Flux/pole
V_a	Armature voltage
$_P$	Pedal pad
$_B$	Braking
b	Booster
$\boldsymbol{L}$	Left tooth flank
$_M$	Master cylinder
R	Right tooth flank
$_0$	Initial or first
$_f$	Frontal of the vehicle
$_{rb}$	External (out) force on rack or booster
e	Electric

1 Introduction

A hybrid vehicle is a vehicle that uses two or more distinct power sources to move. Hybrid electric vehicles combine an internal combustion engine and one or more electric motors. However, other mechanisms to capture and utilize energy are included. This system can use another fuel that they are good alternative to fossil fuel. In electronic hybrid vehicles, the combustors are used in the auxiliary power unit (APU) in order to generate electric energy with the least pollution. Storing recovery energy by the regenerative braking system in these types of vehicles is used till waste energy reduces [1–3].

In these vehicles energy can be reproduced by using the regenerative braking system, electrical (motor) acts as the generator, which stores recovery energy to battery, flywheel and energy capacitors. This stored energy reduces the primary required energy for vehicle movement, so for increase in efficiency. The recovery kinetic energy can compensate the waste energy that is produced by resistive forces of vehicle, e.g., air drag force, and also faster the stop is one of its advantages which generate more energy. The first model of this system was installed on front of differential gear vehicles by Mr. Louis Antoine Krieger, and then this system was used in electric railways in England. A number of studies made on this subject, e.g., Moore [1] carried out design of a prototype braking simulator. He carefully evaluated braking system performance. Gao et al. [4] proposed an electronically controlled braking system for EV and HEV, which contained regenerative braking. Among other works carried out [5], design of a magnetic braking system was proposed to design the braking systems to improve the shortcomings of the conventional braking systems. And Yimin Gao et al. [6] investigated braking energy characteristics on vehicle speed and braking power in typical urban driving cycles. Kim et al. [7] studied the characteristic of the fuel cell and the battery according to the SoC state and the regenerative braking by using a generator for a hybrid system with a PEMFC and Ni/MH battery. Ramakrishnan et al. [8] theoretically investigated the effect of system parameters in series hydraulic hybrid system with hydrostatic regenerative braking. In this work, based on the above-mentioned studies, regenerative braking system has been implemented in an urban vehicle and its efficiency has been investigated.

2 Regenerative braking system performance

The regenerative brake involves using an electric motor as electric generator. In electric railways the generated electricity is fed back into the supply system, whereas in battery electric and hybrid electric vehicles, the energy is stored chemically in a battery, electrically in a bank of capacitors, or mechanically in a rotating flywheel. Hydraulic hybrid vehicles use hydraulic motors and store energy in form of compressed air. Vehicles driven by electric motors use the motor as a generator when using regenerative braking; it is operated as a generator during braking and its output is supplied to an electrical load; the transfer of energy to the load provides the braking effect. Regenerative braking is used on hybrid gas/electric automobiles to regenerate some of the energy lost during stopping. This energy is saved in a storage battery and can later be used as energy source of the motor whenever the car is in electric mode.

While the vehicle is braking and the needed force of braking is less than the maximum force of regenerative brake supplied by the electric system; in this case, electric engine acts as a generator to generate the braking

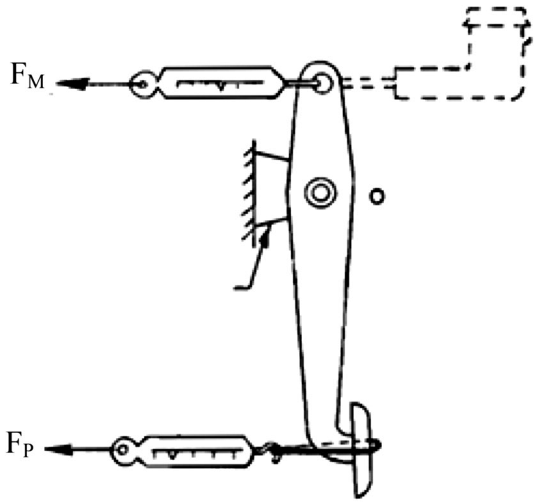

Fig. 1 Forces acting on braking pedal

force equal to needed braking force. In such a condition, the internal fuel engine is off or it is neutral; in this case, if the needed braking force is more than maximum regenerative braking force, mechanical brake would be used, and the maximum regenerative force would be generated in the electric motor and the rest of braking force would be supplied with the mechanical braking system would [2].

2.1 The components of regenerative braking system

The components of this system are divided into three main parts as following:

- Energy storage device is used to conserve the reproduced energy in braking on till when it is reused including battery.
- Power transmission, is used to transmit the energy of gears to the storage device, the axial powers and generator could be mentioned here.
- Braking controller or driver, is used to identify the hard brakes [2].

3 Analysis mechanical

3.1 Forces acting on pedal

According to Fig. 1 following equation can be written:

$$F_M = F_P \cdot C \tag{1}$$

In this equation F_M, F_P and C are force on master cylinder, force on pedal pad and pedal ratio. And the other known, for achieving to booster out force, booster force must be added to pedal force [9, 10]:

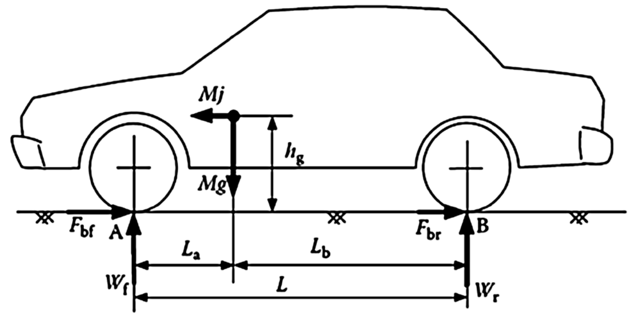

Fig. 2 Forces acting on the vehicle along braking [2]

$$F_{rb} = F_M + F_B \tag{2}$$

$$F_B = \Delta P \cdot A_b. \tag{3}$$

3.2 Braking power and factors and parameters used in the design of regenerative braking system

The rate of motor power in the vehicle in the cycles is as follows:

$$P_d = \frac{V}{1{,}000}\left(Mg \cdot f_r + \frac{1}{2}\rho_a \cdot D_D \cdot Af \cdot V^2 + M \cdot \delta \cdot \frac{dV}{dt}\right), \tag{4}$$

where dV/dt is negative for deceleration. For $P_d > 0$, the traction wheels accept power from the power plants and push the vehicle forward. In this case, the braking power is zero. In contrast, $P_d < 0$ when braking and the kinetic energy of the vehicle mass are dissipated by the brake system. In this case, the driving power is zero [2]; by using P_d gotten braking distance can be obtained (Fig. 2).

3.3 Braking distance

Braking distance is obtained with mathematical operation at follows [11]:

$$P_d = F_B.V \tag{5}$$

$$E = \frac{1}{2} \cdot M \cdot V^2 \tag{6}$$

$$F = M \cdot a = M \cdot \frac{dV}{dt} \tag{7}$$

$$t_b = \frac{E_0}{P_d} \tag{8}$$

$$X_B = \frac{M}{3P_d} \cdot (V_0)^3. \tag{9}$$

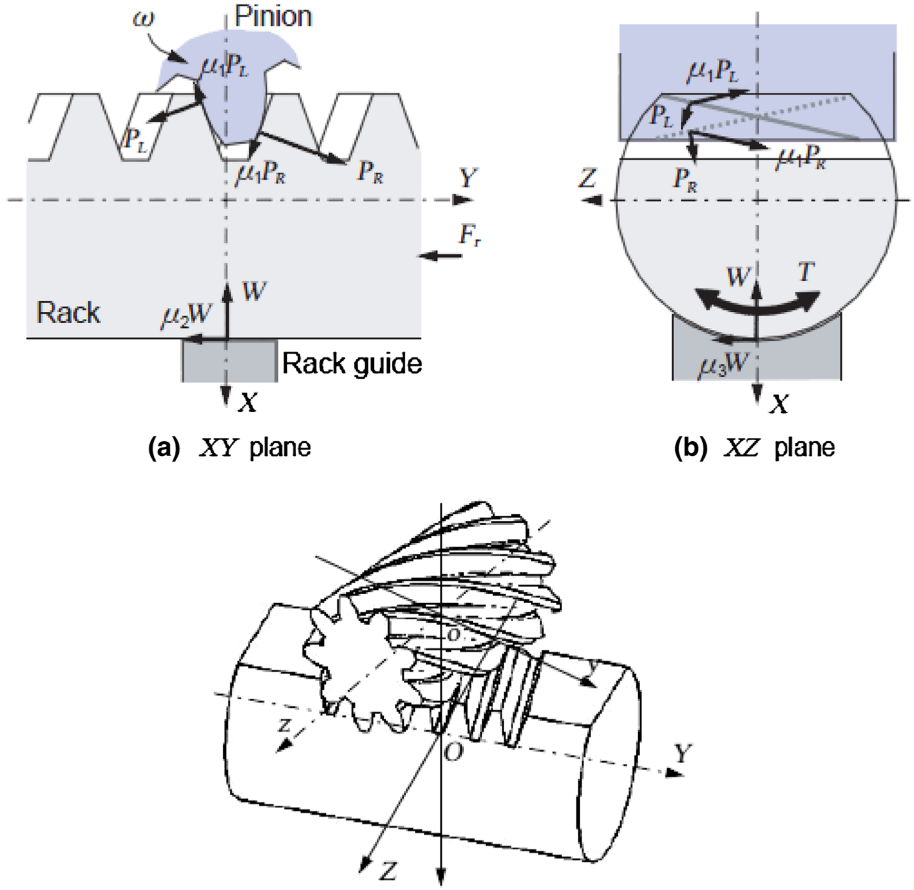

Fig. 3 Exerted Loads on rack [12]

3.4 Forces acting on rack and pinion

In this study for accessing to booster out force is designed pinion and rack gear (Fig. 3).

That $\mathbf{F_{rb}}$ can be calculated by force balance on rack gear, using vector equation below:

$$\mathbf{F_{rb}} = \sum \int \boldsymbol{f}_{\mathrm{R}} dl_{\mathrm{R}} + \sum \int \boldsymbol{f}_{\mathrm{L}} dl_{\mathrm{L}} - \mathbf{W} - \mu_2 \mathbf{W} \tag{10}$$

$$\boldsymbol{f}_{\mathrm{R}} = P_{\mathrm{R}} \boldsymbol{e}_{\mathrm{fR}} \tag{11}$$

$$\boldsymbol{f}_{\mathrm{L}} = P_{\mathrm{L}} \boldsymbol{e}_{\mathrm{fL}}. \tag{12}$$

Writing above equation on the rack axis-direction:

$$\mathrm{F_{rb}} = \sum \int \boldsymbol{f}_{\mathrm{R}} dl_{\mathrm{R}} + \sum \int \boldsymbol{f}_{\mathrm{L}} dl_{\mathrm{L}} - \mu_2 W \frac{\omega}{|\omega|} \tag{13}$$

value of required torque which is provided by electrical motor is found using moment equilibrium on pinion axis:

$$\begin{aligned} \mathrm{T} = & \sum \int \boldsymbol{r} \times \boldsymbol{f}_{\mathrm{L}} dl_{\mathrm{L}} - \sum \int \boldsymbol{r} \times \boldsymbol{f}_{\mathrm{R}} dl_{\mathrm{R}} \\ & + \sum \int \boldsymbol{r} \times \mu_1 \cos\left(\sum\right) \boldsymbol{f}_{\mathrm{L}} dl_{\mathrm{L}} \\ & + \sum \int \boldsymbol{r} \times \mu_1 \cos\left(\sum\right) \boldsymbol{f}_{\mathrm{R}} dl_{\mathrm{R}}. \end{aligned} \tag{14}$$

Now having linear speed of rack, reaction time is calculated using:

$$u = r\omega \frac{\cos \beta_{\mathrm{P}}}{\cos_{\beta_{\mathrm{r}}}} \tag{15}$$

$$\rightarrow t_{\mathrm{R}} = \frac{\Delta x}{u}. \tag{16}$$

Finally using T, F_{C} and t appropriate motor will be chosen [12].

4 Electrical analysis

The behavior of a dc motor can be described by a few simple equations:

$$T_{\mathrm{e}} = K f\, I_{\mathrm{a}} \tag{17}$$

$$E_{\mathrm{e}} = K f\, \omega \tag{18}$$

$$V_{\mathrm{a}} = I_{\mathrm{a}} R_{\mathrm{a}} + E_{\mathrm{e}} \tag{19}$$

$$P_{\mathrm{e}} = T\omega. \tag{20}$$

Note that the same motor constant, K, can only be used in the torque and voltage equations when working in MKS

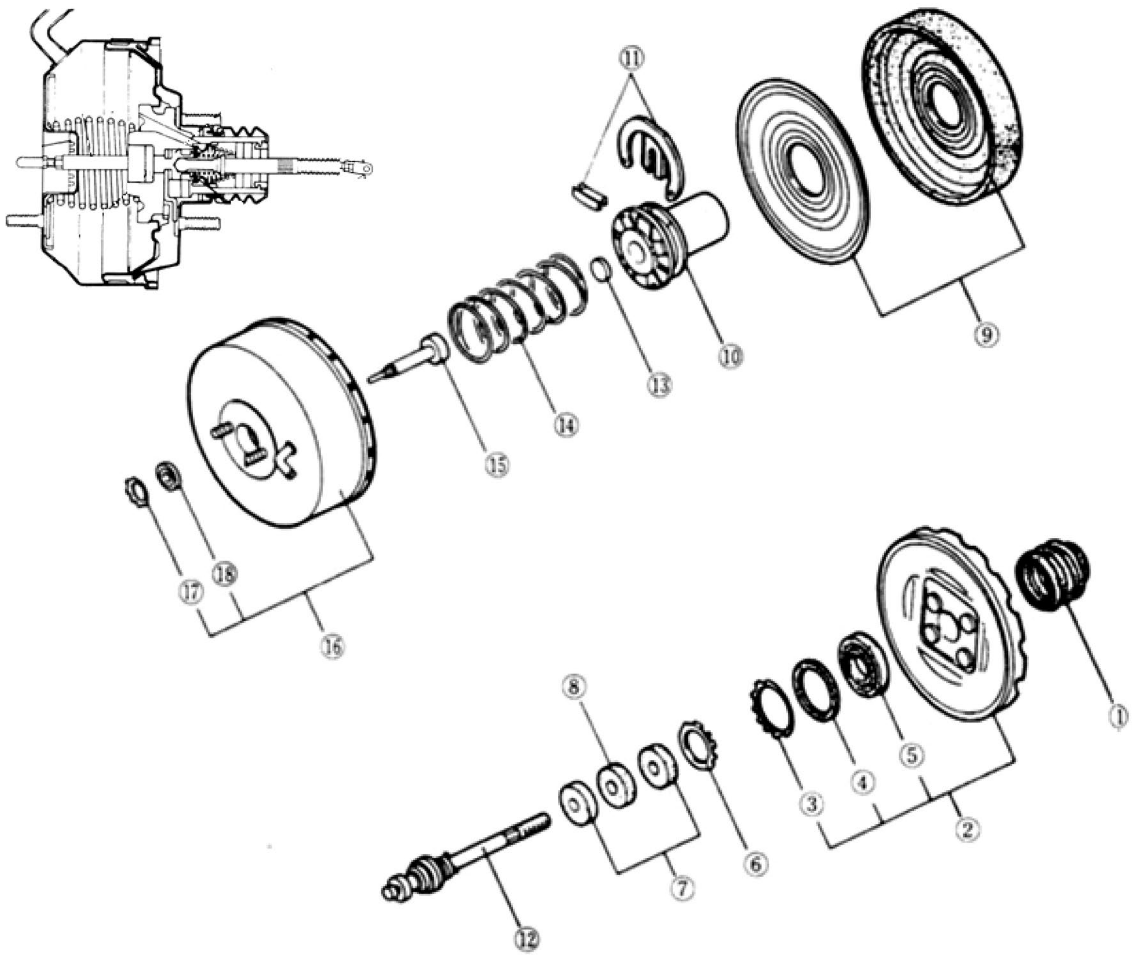

Fig. 4 Components of brake assist system [14]

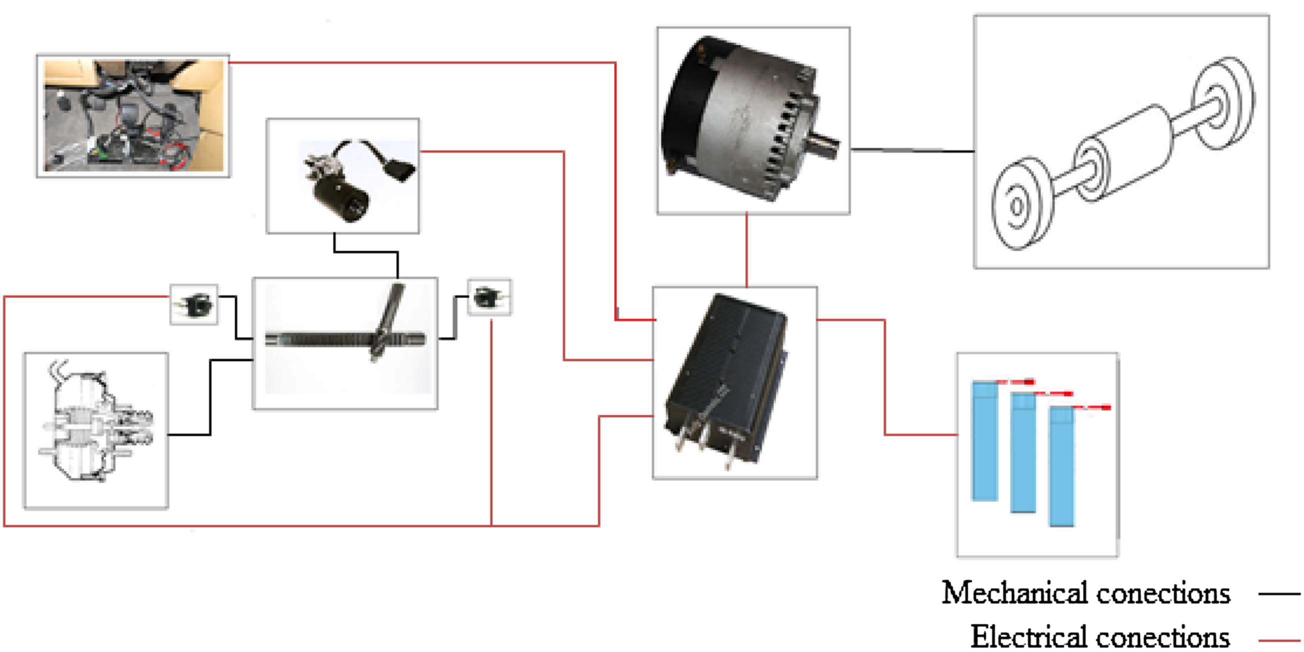

Fig. 5 Brake connections and components are integrated with brake assist systems (regenerative brake)

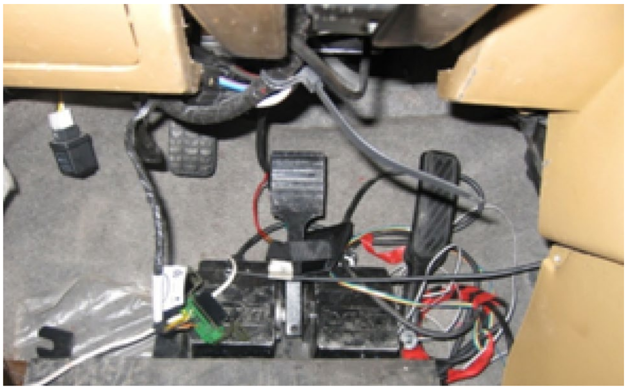

Fig. 6 Electric pedals

units. When using other unit systems adjustments are needed to account for units and separate constants for the voltage and current equation must be used [13].

5 Describe project

According to the previous explanations, the regenerative braking system has been obtained by making some changes in Pride's braking system, whereas the brake designing principles are constant. Since main changes have appeared in the booster system, therefore its introduction is necessary. Components of this system are shown in Fig. 4.

Where 1,2,3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 and 18 are, respectively, the duster, back cortex, back protector, ball bearing, sealed ball bearings, protector, air filter, sound-deadening, diaphragm and chip, power pistons, the protector bristle and the blockage piece, piston and Soupape rod, reaction disc, spring, pressure rod, front cortex, protector, sealed ball bearings.

At first the rod should be cut, so about the added pieces are still in contact. Then one box with a bush would be put in the power piston, therefore it will be fixed. Then the end of box has to be fixed to the rod with fortified washers, while the power piston continues its previous movement, and finally the design of rack and pinion gear should be considered in power transmission. Fixing the pinion on the engine shaft by key and by using involvement between the pinions in the box in the pressure piston, the linear movement of rack is seen with the rotational movement of the pinion which causes the power piston to squeeze and get free. A design of this has been provided in Fig. 5.

As seen in Fig. 5, it has to be stated that in the start and end of allowable range of motion rack, two key mutilators have been inserted which make the process stop and/or change the direction of pinion rotation, before the rack reaches the final allowable range of motion. As mentioned in the design principles for regenerative braking system, the motor movement would be measured by electric pedals with measuring the output voltage strength changes by pedal course, in this case with programming in the machine drive and the recognition of required acceleration reduction with electric pedals and the rate of charge in the batteries, suitable velocity would be given to the motor. Refer to Fig. 6 for this.

To access the velocity of the vehicle, the sensor existing in the output gearbox would be used.

Table 1 Pride's parameters [14, 15]

Item	Symbol	Unit	Value
Vehicle mass	M	kg	1,050 (unloaded)
Rolling resist. coefficient	f_r	–	0.015
Aerodynamic drag coefficient	C_D	–	0.35
Front area	A	m^2	1.792
Wheel base	L	M	2.65
Distance from gravity center to front wheel center	L_a	M M	0.88 (unloaded)
Gravity center height	h_g	M	0.55 (unloaded)
Engine	Type of motor	4—cylinder in line, sohc	
	Max power	Hp	63
Electric motor 	Type of motor	DC (ME1003)	
	Power	kW	11.5 (continuous)
	Volt	V	72
Battery	Model		
	Nominal voltage	–	LIP1034104P-3S3P
	Approximate	v	11.1
	Weight	gr	780

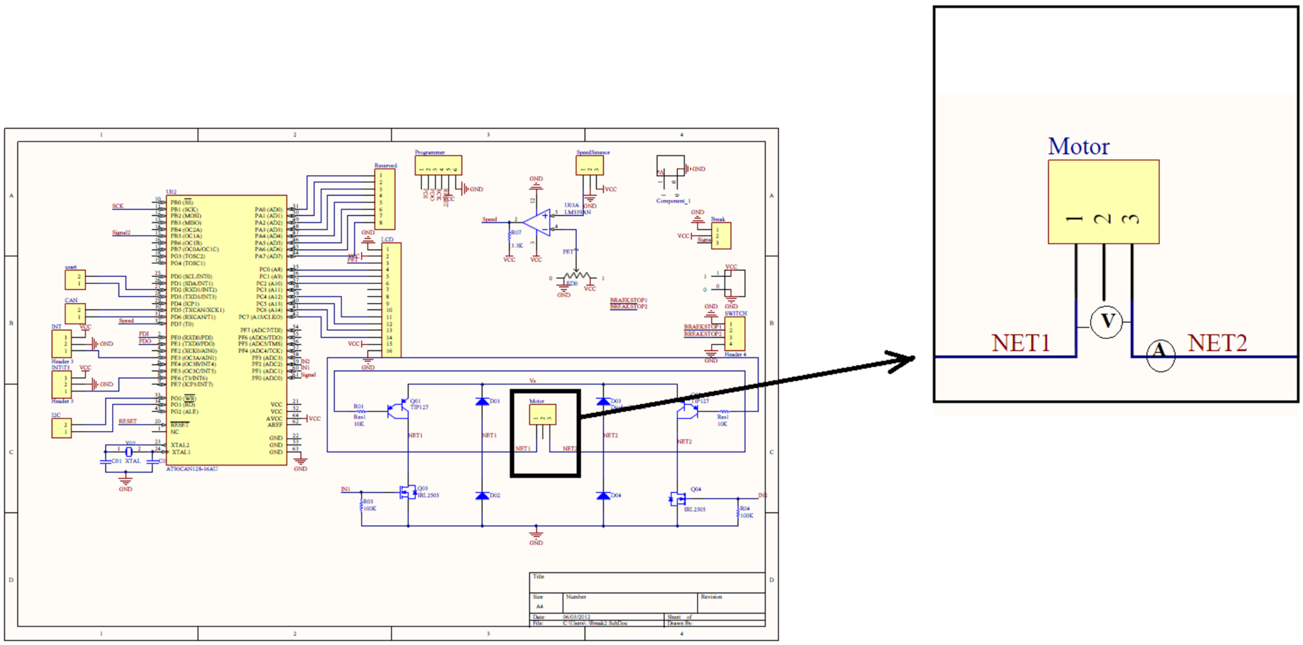

Fig. 7 Electrical circuits and test equipment

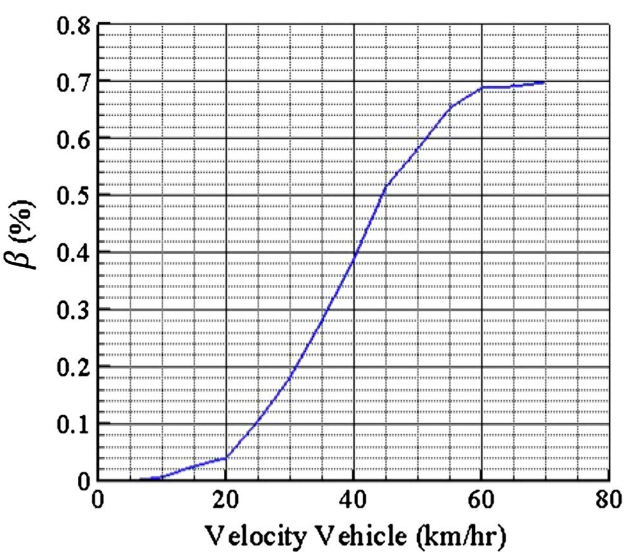

Fig. 8 The ratio of output power percentage to vehicle velocity

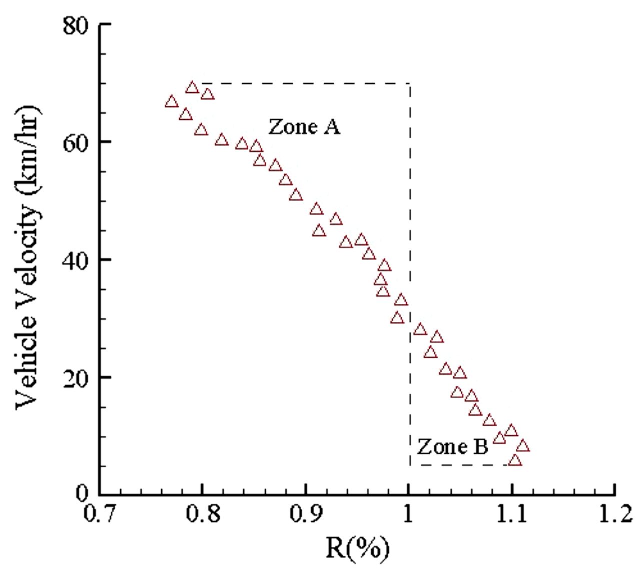

Fig. 9 The braking distance ratio to vehicle velocity

5.1 The selection of electric engine

Since of the reaction velocity in this system has to be very high for braking rapidly, particular attention has to be paid to the selection of motor by which an appropriate velocity for reaction and transmission of the power would be gained, also as known the motor rotational velocity is effective in the braking velocity and motor torque has direct relationship with the transmission power according to Eqs. 13, 14, 15.

6 Case study and results

The case study in this research is "Pride" which is manufactured by Saipa Company, information of which has been shown in Table 1. This vehicle has been evaluated with fixing DC motor that can act as both motor and generator, which changed the vehicle to hybrid vehicle. The regenerative braking system strategy in this research is combined with mechanical brake and electrical brake and

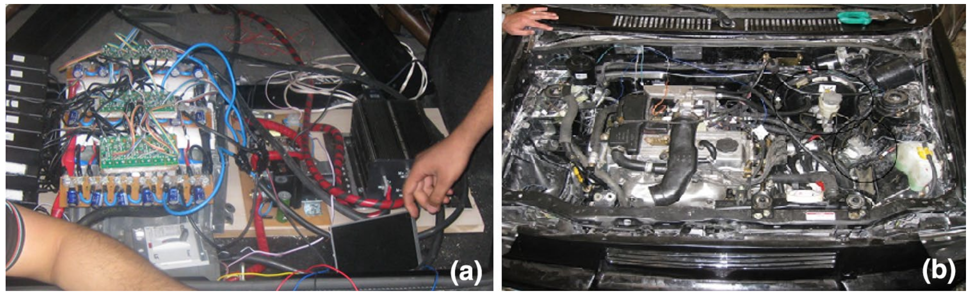

Fig. 10 **a** View of booster and ABS system in vehicle "Pride". **b** View of the controller and batteries in vehicle

when the requested braking force is more than the regenerative braking force, then electric motor generates the maximum braking force and remainder is compensated by mechanical brake system. For a better investigation of the function of regenerative braking system, Figs. 7, 8 and 9 have been used which are experimental results of case study.

Figure 8 shows the relation between regenerative power and utilization power "β" in the same speeds for two modes which is obtained by using certain voltage and current measurement devices which confine the generator or motor.

Dimensionless number, β, according to (4) and (20) is: $\beta = \frac{P}{P_d}$.

The results of this test show, relation between regenerative power and utilization power "β" at the same speed, which is not suitable in low speed and the braking energy; recycling increases with speed augmentation. As a result, it can be said that this system is more suitable for speeds above 20 km/h.

According to the Eq. 9, in following graph is shown R, at speed range of 0–70 km/h for two modes, with regenerative braking system and without it.

$$\text{Dimensionless number, R:R} = \frac{X_{B,\text{regenarative}}}{X_{B,\text{convetional}}}$$

The results of this test show that at low speeds (zone B) the braking distance is more than that of the conventional braking system, because the braking force is generated only by electrical brake and it has a low efficiency, but in high speed (zone A) the braking distance is less than that of conventional braking system because the braking force is generated by both electrical and mechanical braking system. Because of deficit place in hybrid vehicle, the accumulator of ABS system is dislocated. Refer to Fig. 10a.

The Fig. 10a depicts a view of the controller and batteries in hybrid vehicle that have been introduced.

These tests have been done for speed range of 0–70 km/h and the results are valid for this range.

7 Conclusion

The aim of this research is preparation of regenerative braking system for a recycling urban automotive with characteristics in Table 1. According to the results:

- The results of the output power percentage show the braking energy recycle increases with speed augmentation up to 70 km/h and for speeds less than 20 km/h, is very low. Variables such as vehicle speed, battery capacity, generator kind and capacity limit the regenerative power.
- The results of braking distance test show, the hybrid vehicle with regenerative braking system in low speed does not have desirable efficiency because the regenerative energy in this speed is low also the braking distance is more than the conventional state (>1), but since both mechanical brake and electric brake are active in high speed the braking distance will be reduced (<1).

Not determine the scope of the braking situation (according to Sect. 2), reduce the level of battery charge in high speed, the high reaction time designed gears, and problems in clutching system that the coupling between electric motor and wheels is done by clutch, are imperfections of mentioned system. This project with following offers can improve:

- Using the controllers for programming, accurate timing, and the recovery of this system.
- Using the electric motor gearbox to control the motor revolution.

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