DESIGN AND ANALYSIS OF HYDRAULIC IN A HEAVY COMMERCIAL VEHICLE BY RECOVERING ENERGY DURING BRAKING

Setyamartana Parman and Eijaz Zainuddin
Department of Mechanical Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, Perak, Malaysia
E-Mail: setyamartana@petronas.com.my

ABSTRACT

This paper studied a hydraulic regenerative braking in heavy commercial vehicles. The study determined amount of energy that can be recovered during braking period first. The recovered energy came from kinetic energy exerted by the engine when the vehicle is slowing down. Then, the kinetic energy was partially transformed into hydraulic energy to be stored and be used for future acceleration. Only the energy efficiency of the hydraulic regenerative braking system was analysed. The main attention of the paper was focusing on the calculation of thermal energy that can be converted into hydraulic energy in order to be re-used for future acceleration.

Keywords: vehicle, braking, kinetic energy, hydraulic energy, and regenerative system.

INTRODUCTION

Regenerative braking in vehicles has attracted a lot of interest in the last four decades. Such a system is applicable in heavy commercial vehicles those stop and go very frequent, such as in refuse trucks or buses [1]. Energies generated by the combustion engines during the acceleration are wasted into heats and released into the environment when the vehicles brake. Hydraulic Regenerative Braking (HRB) decreases the load on the brakes during deceleration and the load on the combustion engine during acceleration. It leads to a considerable reduction in fuel consumption and brake wear [2].

The first law of thermodynamics claims that energy cannot be destroyed. When a vehicle slows down or decelerates, kinetic energy is converted to thermal energy, i.e. heat. This heat is the product of friction occurred in the brake lining and is considered to be a waste. If this heat wasted occurs again and again for many more years, then the whole world will continue to suffer paying the extra cost of fuel, wear and tear of brakes, and harm towards the environment. Therefore, it is crucial to study the options available to solve this excess kinetic energy problem. In this case, a study on the hydraulic regenerative braking is considered to be an option. This study can be done through designing a hydraulic regenerative braking and doing a simulation on it to obtain the energy efficiency of the system.

In this paper, a hydraulic regenerative braking system for a heavy commercial vehicle is designed. As the vehicle model, Tata LPK-2523 garbage truck is selected. The system to be designed consists of new components and selection of drum brakes, electric controller, engine, axial piston unit, safety relief valve, hydraulic fluid tank, accumulators, drive shafts and axles, pipes and wires. Finally, the energy efficiency of the system will be evaluated.

THEORETICAL REVIEW

Regenerative braking

Regenerative braking is the process of slowing down a vehicle while recapturing as much kinetic energy as possible from being wasted through friction. Energy can be stored electrically and mechanically. Electrically, the energy is stored in a battery. Mechanically, the energy can be in the forms of pneumatics, hydraulic, and rotating flywheel. The energy collected during braking cannot be restored fully during the driving stage. The energy is still wasted through friction with the road surface and other drains on the system. However, it does improve energy efficiency and assist the main alternator [3].

Electric (Battery)

The regenerative brake system can change kinetic energy to recharge the onboard battery as the vehicle slows down or until stops. The charge then powers the vehicle's electric traction motor. This technology is used in Toyota Prius hybrid car [5].

Pneumatic

According to Ricardo [1], the energy dissipated during braking can be stored pneumatically. This can be done by combining conventional dissipative braking with an up-to-date hydro-pneumatic regenerative unit utilizing a fixed displacement pump/motor [4].

Hydraulic

A hydraulic accumulator can save high energy flows in a short time (high power density). Eaton's Hydraulic Launch Assist™ (HLA®) uses a parallel hydraulic system, where the conventional vehicle powertrain is supplemented by the addition of the hydraulic system. Based on the Eaton's concept, during braking, the vehicle's kinetic energy drives the pump/motor as a pump, transferring hydraulic fluid from the low pressure reservoir to a high-pressure accumulator. The fluid then compresses nitrogen gas in the accumulator and pressurizes the system. The regenerative braking captures about 70% of kinetic energy produced during braking. During acceleration, fluid in the high-pressure accumulator is metered out to drive the pump/motor as a motor. The system propels the vehicle by transmitting torque to the driveshaft [6].

Rotating flywheel

A rotating flywheel as the mechanical storage device can accumulate and then release the regenerative braking energy needed for acceleration instead of an electric battery. Physically, the energy in the rotating flywheel can be approximated in a simple mathematical equation:

$$E = Mv^2 \tag{1}$$

where M is the physical mass of the flywheel, and v is the velocity of the spinning mass. The flywheel stores exponentially more energy the heavier it is and the faster it rotates [5].

WORKING PRINCIPLES OF THE HYDRAULIC REGENERATIVE BRAKING SYSTEM

Storing

The hydraulic axial piston unit is coupled to the mechanical drive train through a gearbox. When braking, the axial piston unit converts kinetic energy into hydraulic energy, and pump hydraulic fluid into the pressure accumulator. As result, the pressure in the accumulator increases. When working as a motor, the pressurized hydraulic fluid in the accumulator actuates the axial piston unit. The axial piston unit remains coupled to the mechanical drive train until the pressure accumulator is discharged. The valve manifold controls the filling and discharging process, and protects the accumulator from excess pressure. The electronic controller regulates the hydraulic regenerative braking. In normal drive operation, the hydraulic regenerative braking system is decoupled [7].

Mechanism

A gearbox connects a hydraulic variable axial piston unit to the mechanical drive train. During braking, the piston unit operates as a pump and converts kinetic energy into hydraulic energy by loading a hydraulic bladder accumulator with hydraulic fluid and slows down the vehicle. This process is controlled by an electronic controller together with a hydraulic valve manifold.

During acceleration the entire process is reversed. The pressurized fluid is discharged in a controlled manner from the accumulator and flows back through the variable axial piston unit. The latter is driven by the fluid flow and, acting as a motor, gives up its energy to the mechanical drive train and relieves the existing combustion engine. A pressure relief valve and an electronic monitoring of all safety relevant system and vehicle variables, ensures safety for both processes [8].

Accumulator

Hydraulic accumulator is a simple hydraulic device which stores energy in the form of fluid pressure. It uses either ballast weights, spring, or gas pressure to generate the pre-charge force against the fluid that is stored under pressure for use in the system [9]. Performance of gas can be stated approximately by the formula:

$$P_1V_1 = P_2V_2 = P_3V_3 \tag{2}$$

where P and V represent the absolute pressure and volume of the gas, respectively, and the subscripts represent location of the gas.

An accumulator usually has a cylindrical chamber, which has a piston in it. This piston is either spring loaded or some calculated weight is kept on it or even pneumatically pressurized. The hydraulic pump pumps the fluid into the accumulator, which is nothing but a sealed container. The volume of the container is fixed and cannot be changed. But the quantity of hydraulic fluid being pumped inside the container is increasing continuously. So the pressure of the hydraulic fluid inside the container starts to increase [10].

When using the accumulator as an energy storage element, it is important to deduce the mathematical expression for the total stored energy and the useful energy delivered by the accumulator. The total energy stored in the hydraulic accumulator is the increase in the compressed air energy when compressed from pressure P_0 to P_2 [10]. An expression for this energy could be deduced as:

$$\mathrm{d}E = -\,P\mathrm{d}V \tag{3}$$

The negative sign indicates that the stored energy increases with the decrease of gas volume.

When the accumulator delivers energy, the minimum operating pressure should be sufficient to drive the hydraulic motors and cylinders. The effective energy delivered by the accumulator can be calculated using

$$E_e = P_1\,(V_1 - V_2) \tag{4}$$

Pump

Pumps supply the oil or air under pressure that is required to move the system's cylinder pistons, converting mechanical power to fluid power. The pump displacement is defined as the volume of liquid delivered by the pump per revolution, assuming no leakage and neglecting the effect of oil compressibility. It depends on the maximum and minimum values of the pumping chamber volume, the number of pumping chambers, and the number of pumping strokes per one revolution of the driving shaft. This volume depends on the pump geometry; therefore, it is also called the geometric volume, V_g. It is given by the following equation:

$$V_g = (V_{max} - V_{min})\,z_i \tag{5}$$

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where i is the number of pumping strokes per revolution, V_g is the geometric volume of pump displacement in m^3/rev, Vmax is the maximum chamber volume in m^3, V_{min} is the minimum chamber volume in m^3, and z is the number of pumping chambers.

If there are no internal leakage, friction, and pressure losses, the pump flow rate is given by the following expression:

$$Q_t = V_g n \tag{6}$$

where Q_t is the pump theoretical flow rate in m^3/s and n is the pump speed in rev/s. The input mechanical power is equal to the increase in the fluid power as shown by the following equation:

$$2\pi n T_t = Q_t (P - P_i) = V_g n \Delta p \tag{7}$$

or

$$T_t = V_g \Delta P / 2\pi \tag{8}$$

where T_t is the pump theoretical driving torque in Nm and ΔP is the pressure increase due to pump action in Pa.

The hydraulic power delivered to the fluid by the real pumps is less than the input mechanical power due to the volumetric, friction, and hydraulic losses [10]. The actual pump flow rate, Q is less than the theoretical flow, Q_t mainly due to the internal leakage, pump cavitation and aeration, fluid compressibility and partial filling of the pump due to fluid inertia. The mechanical power, $T\omega$, is converted into equal hydraulic power, pQ_t, then

$$\eta_T = \eta_V \eta_m \eta_h \tag{9}$$

In the steady-state operation, the real displacement pump is described by:

$$Q = V_g n \eta_V \tag{10}$$

$$N_h = N_m \eta_T \quad \text{or} \quad Q\Delta P = 2\pi n T \eta_T \tag{11}$$

Then

$$T_t = V_g \Delta P / 2\pi \eta_m \eta_h \tag{12}$$

where N_h and N_m are the hydraulic and mechanical powers in W, respectively, ΔP is the difference between the pump output and input pressures,

$$\Delta P = P - P_i, \text{ in Pa} \tag{13}$$

If P_i is too small compared with P, then it may be neglected and equation (12) can be simplified as

$$T_t = V_g P / 2\pi \eta_m \eta_h \tag{14}$$

METHODOLOGY

This project reported in this paper consists of design and calculations to obtain the objectives. Various mechanical component of the vehicle like drum brakes, drivetrain, axial piston (motor), electronic controller (pump), and engine are configured using CATIA. Then, the amount of energy that can be recouped in the form of hydraulic energy and transformed back to accelerate the heavy commercial vehicle can be calculated. From these values, the energy efficiency of the hydraulic regenerative braking system can also be obtained.

The calculation takes into account the vehicle mass, desired maximum speed as well as the rolling resistance, efficiency of the mechanical hydraulic regenerative braking components and vehicle drivetrain used by the hydraulic regenerative braking. Additional factors such as drive motor drag torque, air resistance and the energy requirement of the ancillary vehicle systems need to be driven during braking. Then, it calculates the amount of hydraulic energy which the system converts from the mechanical braking energy at the hydraulic regenerative braking drive shaft into hydraulic energy. At the same time, it determines how much mechanical drive energy the stored hydraulic energy creates at the hydraulic regenerative braking drive shaft during acceleration [6]. The equations used for analysis of the accelerating and braking vehicles are tabulated in Table-1 and Table-2, respectively.

Table-1. Equations used for analysis when the vehicle is accelerating.

Step	Parameter
1	Frontal area of garbage truck = Front rectangular area of truck + area of two tires facing in front
2	Overall gear ratio = Final drive ratio + Fixed gear ratio
3	Speed (m/s) = Speed (km/h) / 3.6
4	Force of air resistance = 0.5 x Air friction coefficient x Frontal area of truck x Air density x (speed²)
5	Force of incline = Vehicle mass x 9.8 x (PercentGrade/100)
6	Force of rolling resistance = Vehicle mass x 9.81 x (Brake and Steering Resistance + Tire Rolling Resistance Coefficient)
7	Total Drag = Force of air resistance + Force of incline + Force of rolling resistance
8	Power to maintain speed (in W & hp) = Total Drag x speed (m/s) / Drive efficiency [watt] = (Total Drag x speed (m/s) / Drive efficiency) /745.7 [hp]
9	Acceleration = Speed(m/s) / time to accelerate to speed
10	Energy to accelerate to speed (J) = (0.5 x vehicle mass x speed2) / Drive efficiency
11	Power to accelerate to speed = Energy to accelerate to speed (J) / time to accelerate to speed [watt] = (Energy to accelerate to speed (J) / time to accelerate to speed) / 745.7 [hp]
12	Total Power Required = Power to maintain speed (W) + Power to accelerate to speed (W)
13	Motor RPM at speed = (Speed x 60) / (2 x 3.141596 x wheel radius) x (overall gear ratio) or using Engine output calculator

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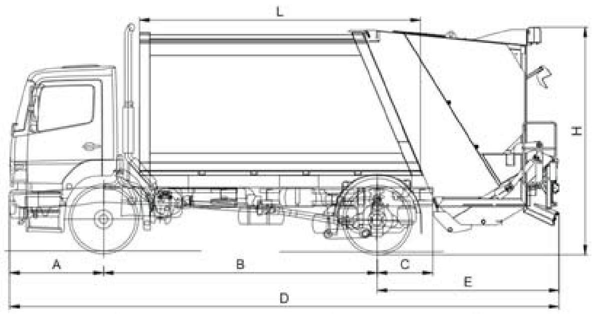
Table-2. Equations used for analysis when the vehicle is braking.

Step	Parameter
1	Force to decelerate = - Speed(m/s) / time to accelerate to speed
2	Total Force during deceleration = Total Drag + Force to decelerate
3	Power during deceleration = Total Force during deceleration x speed (m/s)
4	Heat lost = Engine output (W) + Power during deceleration (W)
5	Hydraulic Energy (Energy Recovered) (W) = Pump flow rate (m^3/s) x Pressure (Pa)
6	Final heat wasted (W) = Heat lost – Energy Recovered
7	% Energy recovered = Hydraulic Energy (W) x 100 / Engine output (W)

DESIGN OF REGENERATIVE BRAKING SYSTEM FOR HEAVY VEHICLE

Tata LPK-2523 garbage truck is selected as the model of heavy vehicle in this paper. The dimension of the garbage truck is shown in the Figure-1. The proposed hydraulic regenerative braking system consists of mechanical components and an electrical component which are engine axial piston unit, safety relief valve, accumulators and an electric controller. The dimensions of the designed drivetrain and axles are considering to the size of the garbage truck. The configuration of the proposed hydraulic regenerative braking system is shown in Figure-2.



A	1.30 m
B	3.80 m
C	0.75 m
D	7.50 m
E	2.50 m
H	3.30 m
L	3.60 m
Front Width	2.50 m

Figure-1. A garbage truck with dimensions.

The system consists of several parts. The first parts are drum brakes. There are four drum brakes in the hydraulic regenerative braking system. Two brakes are in front –right and left– and another two ones are at the rear – also right and left–. The four drum brakes resemble the conventional braking system that this particular garbage truck has. Although this project promotes the significance of a hydraulic regenerative braking system, the conventional braking system still has to be installed in the garbage truck. The reason being that the hydraulic regenerative braking system acts as a second braking system in the vehicle. The working principle of a drum brake is the shoes presses against a spinning surface. For garbage trucks, all front and back utilizes drum brakes as they are cheaper compared to using disc brakes.

Electric controller is becoming the second part. The electric controller functions in conjunction with the brake pedal. When the brake pedal is pressed, this device will send signals to the Axial Piston Unit to either act as a pump. Thus, when the pedal is released, the piston unit will act as a motor to help the vehicle accelerate. The electronic control device ensures that the HRB runs safely, efficiently and comfortably at all times.

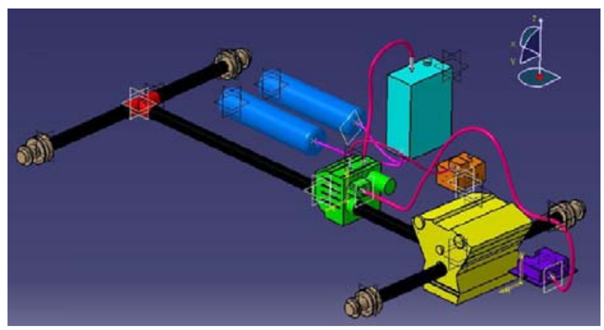


Figure-2. The proposed hydraulic regenerative braking system.

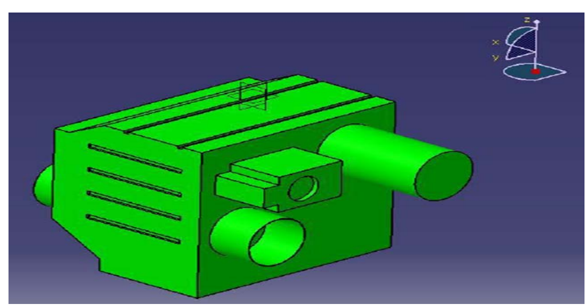


Figure-3. Axial piston unit (Pump/Motor).

The third part is an engine. The 5.8l engine Tata LPK-2523 engine is still maintained. The maximum engine output is 232 HP at 2500 rpm. The axial piston unit as shown in Figure-3 and accumulators become the fourth and fifth components. During braking, the hydraulic axial piston unit coupled to the mechanical drivetrain converts kinetic braking energy into hydraulic energy. It acts like a pump and fills a hydraulic membrane type accumulator with hydraulic fluid. Fluid is transformed from the low pressure reservoir to a high-pressure accumulator. The

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fluid compresses nitrogen gas in the accumulator and pressurizes the system.

When accelerating, the pressurized fluid is evacuated from the accumulator and flow back through the axial piston. The piston unit is driven by the fluid flow and acts like a motor. It transmits its power to the mechanical drivetrain. The Bosch Rexroth axial piston is selected in this paper. It may produce 233 kW maximum power and 1.113 Nm maximum torque. As the accumulator, the one produced by similar company is selected. It can control an acceleration torque of up to 2500 Nm, while the volume is 2 × 32 litres.

Data for axial piston unit that will be used for the analysis is as follows:

- ✓ Pump Displacement = 210 ccm
- ✓ Max. Engine Output = 232 hp
- ✓ Max. Rpm = 2500 rpm
- ✓ Min Hydraulic Power = 25200 W
- ✓ Max Hydraulic Power = 68250 W
- ✓ Mechanical efficiency of pump = 0.7
- ✓ Hydraulic efficiency of pump = 0.7

The sixth component is a relief valve. This valve is to make sure the fluid pressure transferred to the accumulator does not exceed its pressure limit. It controls the flow of oil and ensures through a pressure control valve that at no given time excess pressure occurs in the system. This safety valve protects the hydraulic regenerative braking system so that it maintains the flow of hydraulic fluid at an optimal pressure. The valve is shown in Figure-4.

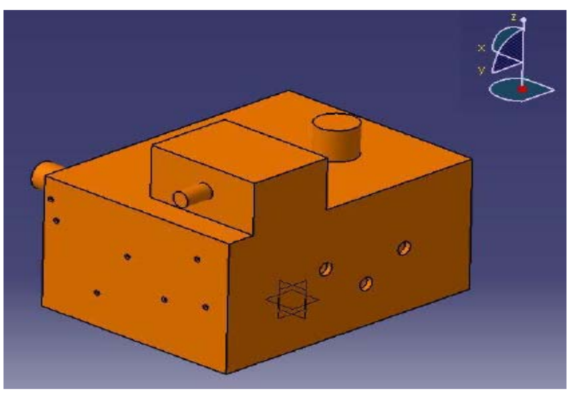

Figure-4. Safety relief valve.

The seventh component is the hydraulic liquid tank. The purpose of this hydraulic fluid tank is to act as a fluid reservoir and store the hydraulic fluid. The tank also maintains as a low pressure reservoir. To accommodate the fluid quantity, the volume of this tank is selected larger than 64 litres. The last component are drive shafts and axles. These components consist of two drive shafts –front and Rear– and two axles. One axle is connecting the engine with the piston unit, while the other axle is connecting the piston unit with the rear drive shaft.

For the analysis, data for Tata garbage truck model LPK 2523 is used. The data is as follows:

Table-3. Garbage truck data.

Truck frontal area = 4.8 m^2	Drag coefficient = 0.85
Percent grade = 0	Air density = 1.2 kg/m^3
Vehicle mass = 14000 kg	Wheel radius = 0.49 m
Drivetrain efficiency = 1	Final drive ratio = 4.24
Tire rolling resistance coefficient = 0.00953	Fixed gear ratio = 1.36
Brake and steering resistance = 0.003	Overall gear ratio = 5.77

RESULTS AND DISCUSSION

The parameters those are not depending on the vehicle speed in this calculation are forces due to road inclination and rolling resistance. Here, the road inclination is set to be zero, while the rolling resistance force is supposed as 1721 N at all considered speed. With 0.3-m/s^2 desired acceleration, the total required power of engine output as the variation of vehicle speeds can be calculated. Also, the actual motor torque, engine RPM and vehicle acceleration can be found.

The hydraulic power of recovered energy when the vehicle is braking with deceleration 0.3 m/s^2 is shown in Table-4, while the vehicle power during deceleration is listed in Table-5.

Table-4. Recovered hydraulic energy.

Speed (km/h)	10	20	30	40	50	60	70
(m/s)	2.8	5.6	8.3	11.1	13.9	16.7	19.4
Motor RPM at speed (RPM)	1050	1120	1248	1363	1542	1844	2172
Flow Rate(m^3)/s	0.003675	0.00392	0.004368	0.004771	0.005397	0.006454	0.007602
Pressure,(Pa)	7008997	8289322	8165496	8571979	8783660	9042658	9347728
Pressure,(kPa)	7008.997	8289.322	8165.496	8571.979	8783.66	9042.658	9347.728
Hydraulic_Power,(W)	25758.07	32494.14	35666.89	40892.63	47405.41	58361.32	71061.43

Table-5. Vehicle power during deceleration.

Speed (km/h)	10	20	30	40	50	60	70
(m/s)	2.8	5.6	8.3	11.1	13.9	16.7	19.4
Force to decelerate(N)	-3888.89	-4861.11	-4666.67	-4861.11	-4861.11	-4861.11	-4861.11
ForceTotalDeceleration(N)	-2149	-3065	-2776	-2838	-2668	-2460	-2215
Power during deceleration(W)	-5969	-17028	-23131	-31535	-37057	-41002	-43072

Finally, the recovered power can be calculated. The results are plotted in Figure-5. By installing the hydraulic regenerative braking system in Tata LPK-2523 garbage truck, we can recover the energy lost. With 0.3-m/s^2 deceleration in braking, the energy lost at any speed from 70 m/s to 10 m/s can be recovered partially. The higher the speed of truck when braking is, the greater the energy per second that can be recovered will be. In percentage, the value is in the range of 38 – 43% compared to the engine output.

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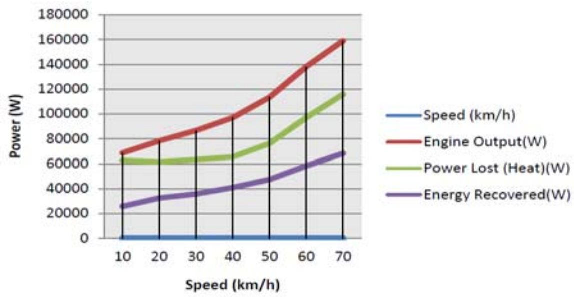

Figure-5. Engine output and recovered energy.

CONCLUSIONS

The hydraulic regenerative braking in heavy commercial vehicles seems to be a promising approach to improve the automotive industry. The hydraulic regenerative braking system can be applied to a lot more commercial vehicles around as it is expected to make use of the useless heat dissipated from normal braking. Furthermore, it may well prove to reduce emissions of the engine and improve fuel consumption of the vehicle. Emissions and fuel consumptions are improved because the usage of vehicle engine is reduced by the pump/motor of the hydraulic regenerative braking system. Another advantage that this system may show is the reduction in braking wear and maintenance. This is because the slowing down mechanism of the heavy commercial vehicle by normal braking system is being assisted by the hydraulic regenerative braking system.

The hydraulic regenerative braking system showed to become a promising technology that should be developed and installed in heavy commercial vehicles. The installation seems to be realistic as the components used for this braking system is mostly simple mechanical components, i.e. piston unit of pump or motor, pressure relief valve, and accumulators. Installing the hydraulic regenerative braking system in the garbage truck which was studied in this paper, considering a city drive process, an average of 40% of the engine power released can be stored and used. Although not all wasted energy can be recovered, this technology can reduce fuel consumption, emission, brake wear and tear and can improve propelling of a vehicle.

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