ENERGY EFFICIENT LIGHTER WEIGHT ALUMINIUM MATRIX COMPOSITE AUTOMOTIVE BRAKE ROTOR

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ABSTRACT

With 75 percent of fuel consumption relating directly to vehicle weight, potential weight reductions that can result in improved performance ratio and reduce CO_2 emissions stimulate the application of lightweight materials. The substitution of aluminium matrix composite (AMC) for structural component of brake rotor is quite effective in lightening, energy efficiency and hence mitigation of global warming. Mathematical models are used to evaluate the influence of light weight material on energy and the environment. This study attempts to predict the effect of weight reduction on energy consumption and CO_2 emissions by replacing conventional materials for light weight AMC. The study found that a weight savings of 50 to 60% from the AMC brake rotor can translate to an energy savings of 16-18% in energy usage and hence reduction in CO_2 emission in the environment. This study will facilitate a cleaner and healthier environment for human life in the society.

1. INTRODUCTION

Vehicle weight reduction is a promising strategy for improving energy consumption in vehicles, and presents an important opportunity to reduce energy use in the transportation sector. The total energy use, weight reduction and emissions of carbon dioxide CO_2 are closely related. Petroleum fuels account for more than 95% of energy use in transport with 75% resulting from vehicle weight in nearly every IEA country, and oil combustion is a major source of CO_2 emissions [1]. The use of road vehicles is estimated to account for 10% of man-made global green house gas (GHG) emissions. This figure is set to grow, as the automotive sector is one of the fastest growing sectors. The number of cars produced worldwide in 2009 was predicted to be over 51 million. With the increasing recognition of weight reduction from the transport industry, improving vehicle fuel economy and emissions are the top challenges facing the industry [2, 3].

Emissions of CO_2 from road transport increased more than in any other subsector between 1990 and 1999 as shown in Fig. 1, for several reasons. The distance travelled by passenger cars has steadily increased over the period of time. Further, the fuel economy of new passenger vehicles did not improve 1985 and 1995. Although the technical efficiency of vehicle weight reduction has improved steadily over the last 20 years, but consumer preferences for larger, heavier, and more powerful models have offset most of the efficiency gains, yielding little change in energy consumption and CO_2 emissions [4].

The most determining factor in car fuel consumption is the weight of the car. Weight savings in the overall car mass is considered to be a major research focus. Studies have shown that every 10% reduction in the vehicle weight can reduce fuel consumption from 5 to 8% [5, 6]. Dropping 68 kg on average gives an extra mile of driving range per gallon of fuel consumed ~0.423 km/l. In terms of its effect on carbon dioxide emissions, reducing vehicle weight by 100 kg brings a CO_2 reduction of up to 12.5 g/km [7].

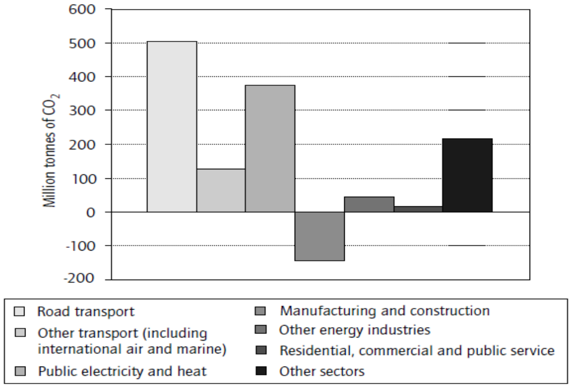

Figure 1. Change in CO2 Emissions by Sector in IEA Countries, 1990-1999 [3]

Earlier studies described that the vehicle fuel consumption reduction benefit associated with light weighting [8]. It is said that the benefit in absolute gains, where the improvement in fuel consumption ranges from 0.15–0.70 L/100km for every 100 kg of weight reduction. Factors that affect this relationship include the size and type of vehicle, the drive cycle used to evaluate the vehicle, and the power train. Anup et, al, [9] was interested in the effect of vehicle weight reduction on its fuel consumption, at constant performance and size, for the average new vehicles. The simulations result revealed that for every 10% weight reduction from the average new car, the vehicle's fuel consumption reduced by 6.9%.Reducing weight can improve the price-to-performance ratio of transportation systems. Novel innovative lightweight materials provide avenues to produce increased fuel efficiency and reduced emission of harmful pollutants, without compromising on performance and size and the study showed that 20% weight reduction could yield 12–14% fuel economy improvement [10].

The information on energy savings in automotive application for lighter weight brake rotor component is not available in the literature. In this study, an attempt to mathematically relate the energy savings possibilities in vehicle weight reduction brought by lighter weight AMC automotive brake rotor and the influence on the energy efficiency for passenger cars.

2. VEHICLE WEIGHT AND ENERGY

The scenario of potential energy savings from reducing the energy needed at the brake rotor of a vehicle can be seen in Fig. 2. The following reasoning would lead to the estimation of energy savings from having a lighter vehicle [11].

i. The ratio of energy converted from fuel to that of the output of an engine is independent of the weight of the vehicle. It is determined by the characteristics (efficiency) of the engine.
ii.The amount of energy lost to idling would also be independent of the weight of the vehicle.
iii.It is dependent on the driving conditions.

The energy used at the rotor of a vehicle on the other hand is dependent on the weight of the vehicle. If the percentage of energy produced by the engine that is transmitted to the brake rotor is X, the previous statements would mean that the percentage of fuel used to produce energy at the wheel rotor (instead of being used for idling) is also X. From this, it can be estimated that the percentage of energy used at the wheel rotor which can be attributed to the vehicle's weight. With this, it can be estimated the possible energy savings from having a lighter vehicle.

Considering the lighter weight AMC brake rotor for a vehicle, the usage of energy consists of three unique components [12]:
1) The acceleration of the vehicle
2) To overcome aerodynamic forces
3) To overcome other losses (rolling friction, wheel bearing friction and etc),

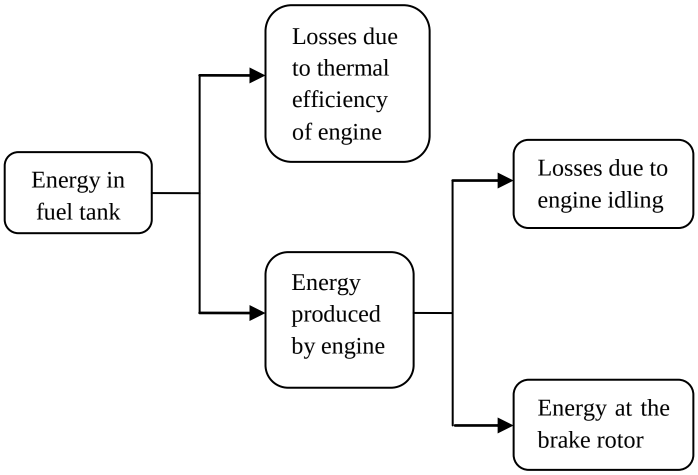

Figure 2 Energy savings from reducing energy at the brake rotor

Then it can be stated that total energy usage of a vehicle through a certain journey is:

$$E_T = E_k + E_a + E_f \qquad (1)$$

where;
E_T is the total energy used (at the wheel) of a vehicle
E_k is the energy used to provide kinetic energy for a vehicle
E_a represents energy used to overcome aerodynamic forces
E_f represents other losses at the wheel rotor

The total energy used at the brake rotor of a vehicle is directly related to the brake power produced by the engine after subtracting losses through the transmission, differentials and torque convertor (if it is an automatic vehicle). When a vehicle is accelerating, energy from the engine is converted into kinetic energy stored in the mass of the vehicle. If a vehicle is halted by applying the brakes, all of these energies will be converted into the form of heat at the brake rotor and pads. This means all of these energies are wasted.

However, if the car is brought to a halt by simply allowing it roll until it stops and the car rolls to a halt without applying the brakes, the kinetic energy stored will in turn be used to overcome whatever resistance (wind and rolling) throughout the decelerating distance and hence it should not be considered a waste. It can then be assumed that a large portion that is 80% of energy used to accelerate the vehicle is wasted as heat in the brake system.

3. HEAT TRANSFER PHENOMEN IN ROTOR

The governing equation for the heat generated due to friction between the brake rotor pad and surfaces as shown in Fig. 3 (a) and (b) is estimated by:

$$dH = dP = VdF_f = qdA = r\omega\mu p\emptyset_0 r\mathrm{d}r \quad (2)$$

$$dH = dH_P + dH_R \quad (3)$$

$$dH_P = (1 - \sigma)dP = (1 - \sigma)\ \omega\mu p\emptyset_0 r^2\mathrm{d}r \quad (4)$$

$$dH_R = \sigma dP = \sigma\mu p\omega\emptyset_0 r^2\mathrm{d}r \quad (5)$$

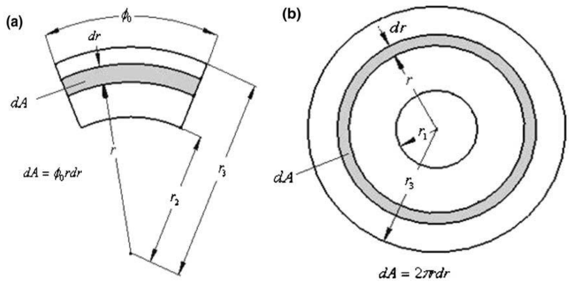

Fig. 3 Contact surface element; (a) pad and (b) rotor

where dH is the rate of heat generated due to friction between two sliding components, V is the relative sliding velocity, $\mathrm{d}F_f$ is friction coefficient, μ is coefficient of friction, ω is angular velocity, p is contact pressure, σ is heat transfer coefficient, $\emptyset_0$ is pad angle, r is the radial position. The terms $\mathrm{d}H_{\mathrm{P}}$ and $\mathrm{d}H_{\mathrm{R}}$ are the amount of absorbed heat by the pad and the rotor respectively.

4. ENERGY USAGE BY AMC BRAKE ROTOR

To estimate the savings achieved by reducing the weight of a vehicle it should first find out how much energy used in a journey is lost due to the weight of a vehicle. The frictional loses due to the rolling resistance and the resistance of the wheel bearings could also be attributed mostly due to the weight of the vehicle. The energy used to overcome aerodynamic forces on the other hand has nothing to do with the weight of the vehicle [13]. With this, it can be stated that the energy usage at the rotor of a vehicle contributed by the weight of a vehicle is a large fraction of the kinetic energy component and the rolling resistance component. It can be computed the fraction of energy used due to a vehicle's weight. If it is assumed that weight has an 80 percent contribution to the kinetic energy losses and the rolling resistance losses, then the ratio of energy used at the brake system which is attributable to weight can be expressed as:

$$R = 0.8\ (E_k + E_f)/\ E_T \quad (6)$$

To obtain an idea of how the range of R is bound to be, it can be analysed in a simplified driving situation. For the following calculation, the driving conditions are as follows: A driver accelerates to a certain velocity v and drives at this velocity for a period; T. After this period T, the driver presses on his brakes and stop to a standstill. This process is then repeated through the journey. This is a simplified analysis to enable one to perform a mathematical estimation of the value of R as mentioned above. However, even though this scenario is simplified, a real driving situation is similar to this and would have an average value of T and v for a certain journey. These values would depend on the driving conditions and the journey. Using this simplified assumption, the energy spent to provide kinetic energy in one acceleration – deceleration cycle can be expressed as:

$$\mathrm{E_k = mv^2/2} \quad (7)$$

The energy lost to aerodynamic forces in one cycle is (assuming the car travelled at an average speed v and the period T is long enough to render the acceleration and deceleration portion of this cycle insignificant. This can be expressed as:

$$E_a = 1/2C_d\rho AV^3T \quad (8)$$

where C_d is the drag coefficient of a certain vehicle, A is the frontal area of the vehicle, ρ is the density of air and v is the average velocity of the vehicle. This term is derived from the aerodynamic force; $1/2C_d\rho AV^2$ multiplied by the velocity V of the vehicle (which gives power) and with the period, T of one acceleration – deceleration cycle. If it is assumed that rolling resistance takes up nearly all the other energy from the wheels apart from the kinetic energy and aerodynamic losses, and that the rolling resistance depends only on the normal force acting on the wheels [14], then it can be expressed as:

$$E_f = C_{rr}W_vT \quad (9)$$

where C_{rr} is the coefficient of rolling resistance and W is the weight of the vehicle.

When equation (7), (8) and (9) is replaced into equation (1); The total energy usage in one acceleration – deceleration cycle;

$$E_T = \mathrm{mv^2/2} + 1/2C_d\rho AV^3T + C_{rr}mgvT \quad (10)$$

Equation (6) can then be rewritten as;

$$R = \frac{0.8\,(mv^2/2 + C_{rr}mgvT)}{mv^2/2 + 1/2C_d\rho AV^3T + C_{rr}mgvT} \qquad (11)$$

The specification for the 1.8 litres variant of the Proton Waja car is as shown in Table 1.

Table 1 Specifications for 1.8 litre Proton Waja (Anon, 2008)

Parameters	**Value**
Curb mass (kg)	1250
Height (m)	1.42
Width (m)	1.74
Frontal area (m^2)	2.47
Drag coefficient	0.30

Using the data in Table 1, the equation 11 can be simplified as follows;

$$R = \frac{500v^2 + 147.2vT}{625v^2 + 0.6819v^3 + 183.9vT} \qquad (12)$$

**The value of C_{rr} is assumed to be 0.015* (Anon, 2006).

Assuming for a certain driving condition, the fraction of energy at the wheel rotor that is attributed directly to the weight of the vehicle is 0.4. Assuming that 70 percent of the energy produced by the vehicle goes to the drive train and 30 percent is lost during idling and to run the engine accessories. This would mean that if the vehicle weight contributes to 40 percent of the energy usage at the AMC brake rotor.

5. ENERGY SAVINGS BY LIGHTER WEIGHT AMC BRAKE ROTOR

Figure 4 shows an example of the energy flow diagram of a modern vehicle. In the Fig.4, the energy diagram represents a vehicle driven in an urban condition while the Fig. 5 represents the energy flow diagram for a vehicle driven on the highway. To analyze these diagrams, it can be seen that the brake output of an engine irrespective of what power is used for would be the sum of the standby energy, the energy used for accessories and the energy supplied the driveline. From these diagrams, the percentage of fuel attributed to the rolling resistance and the braking of the vehicle, could be used for earlier assumptions.

The rolling and braking resistance from the Fig. 4 sums up to be about 75 percent of the energy used at the wheel rotor. If the driveline losses is simply a constant factor of the amount of energy delivered to the driveline, the percentage of energy to the driveline being used to overcome the rolling resistance plus the braking would also be equal to 75 percent. The mechanical energy produced by the engine for the Fig. 4 would be the sum of the energy used at standby, the energy used by the accessories, and the energy supplied to the driveline. From these, the percentage of mechanical energy produced by the engine which is sent to the drive line would be 50 percent.

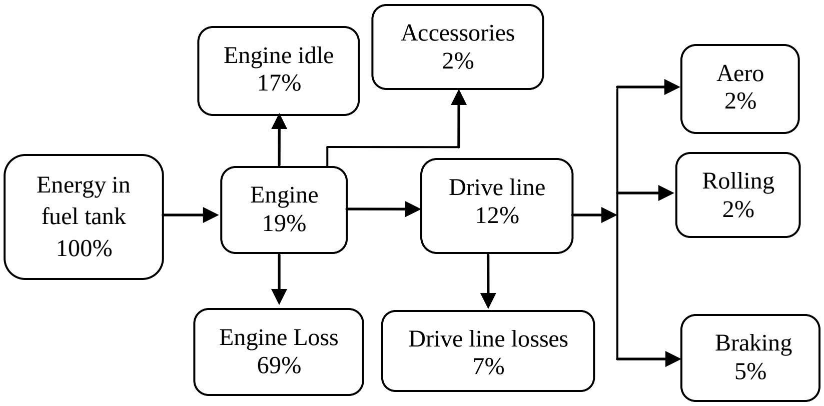

Fig. 4 Energy flow diagram for a vehicle driven in an urban condition

Assuming that the amount of engine losses is always a fixed percentage of the amount of mechanical energy produced by the engine, it can be concluded that the fraction of fuel which is used to overcome rolling resistance and braking losses is:

$$0.749 \text{ X } 0.50 = 0.3745$$

If it is further assumed that 80 percent of this percentage could be attributed to the weight of the vehicle, the amount of fuel used attributed to the vehicle's weight is can be calculated as 0.3076 or 30.76% ~31%. A similar calculation for the Fig. 6 (highway driving) would result in 29% energy savings.

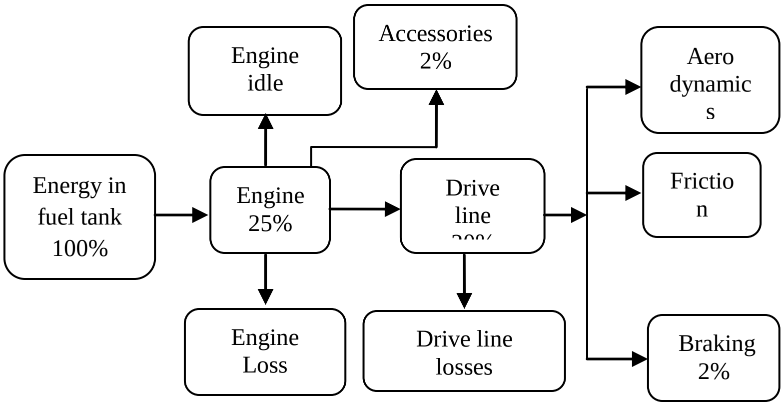

Fig. 5 Energy flow diagram for a vehicle driven on the highway

6. CONCLUSIONS

The following conclusions can be drawn from the present study;

- (i) the amount of energy used in a vehicle that can be attributed to weight reduction is about 30% with a potential energy savings of 9%.
- (ii) the application of lighter weight AMC brake rotor with a potential of 50-60% weight reduction can translate to an energy savings of 16-18%.
- (iii) the reduction in weight and energy savings influences the amount of CO_2 emitted to the environment as a whole.
- (iv) This study will facilitate the usage of AMC as a light weight material for brake rotor application.

7. ACKNOWLEDGEMENT

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