Review

Improvement of Fuel Efficiency of Passenger Cars by Taking Advantage of Tribology

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Abstract

The study conducted by a study group on the prediction of car fuel savings realized through tribology development organized by the Japan Society of Tribologists showed that the fuel loss caused by tires was 7.5% for constant velocity running at 60 km/h. Furthermore, the Japan Automobile Tyre Manufacturers Association estimates that the contribution rate of the reduction in tire rolling resistance to fuel savings is between 20 to 25% in the case of constant velocity running, and these figures cannot be explained if we consider the fuel loss of tires alone. The study group adopted a threefold improvement in fuel economy, as it reduces both the exhaust and cooling losses in the same ratio. In addition, the study group proposed a novel retroactive effect, which states that reduction of downstream elements’ losses decreases the upstream elements’ losses. The contribution rates of the individual elements to the fuel consumption can be calculated by taking the threefold improvement and the retroactive effect into consideration.

Keywords

tribology, passenger car, fuel efficiency, improvement, power train, retroactive effect

1 Introduction

At the G7 Summit in 2015, the Japanese government declared that carbon dioxide emissions would be reduced by 26% from 2013 to 2030. The efforts to reduce the global warming gases must be continued despite the disaster of the Fukushima Daiichi Nuclear Power Plant. The main applications through which tribologists can contribute to the reduction of carbon dioxide emissions are manufacturing and transportation equipment. In this paper, an improvement in the fuel efficiency of passenger cars that is realized by using advantage of tribology is discussed. This paper presents the results obtained by a study group, from the Japanese Society of Tribologists (JAST), that conducted a study on the prediction of car fuel savings realized through tribology development. The study group consisted of researchers from automobile manufacturers, car-parts manufacturers, and universities and predicted an improvement in the fuel efficiency of passenger cars that will be produced in 2020 as compared with cars produced in 2010 [1]. The researchers from car parts manufacturers proposed reduction rates in friction losses of power train elements based not only on technical possibilities but also on marketability. It was a heated argument to estimate the effects of the friction loss reduction on the fuel consumption of the passenger car. Holmberg et al. reported that reductions in frictional losses have a threefold improvement in fuel economy, as it reduces both the exhaust and cooling losses also in the same ratio [2]. The study group engaged in an exhaustive discussion on the exhaust and cooling losses of the engine and finally concluded that the exhaust and cooling losses are reduced in the same ratio of the total friction loss reduction (threefold improvement.) Furthermore, the study group conceived of a retroactive effect [3], which was the reduction in the upstream element losses due to the reductions in the downstream element losses. The contribution rates of the individual power train elements to the fuel consumption can be calculated by taking the threefold improvement and the retroactive effect into consideration.

2 Standard passenger car 2010 in Japan

The study group, which was established in 2011, selected a standard passenger car in Japan as shown in Table 1. The
standard passenger car was manufactured in 2010. Table 1 shows the specifications of the standard passenger car (Car 2010) and its running condition. It is assumed that the fuel consumption is 20 km/L (5 L/100 km) for a constant running velocity of 60 km/h on a paved flat road, and this value is used for predicting the fuel consumption of the car in 2020.

3 Share percentage and contribution rate in constant velocity running

3.1 Share percentage and reduction rate in constant velocity running

The study group calculated the share percentage of the fuel consumption of the car elements in the power train from the engine to the tires, and the calculated results are listed in Table 2. The tires’ share percentage of the fuel consumption is the greatest for constant velocity running. The pumping loss of the engine has the second largest fuel consumption percentage because of the relatively low load condition, which causes choking of the throttle valve during the constant velocity running. These results are shown in Fig. 1, with the exhaust and cooling losses of the engine and the air drag. If the total fuel consumption is represented by 100%, the exhaust and cooling losses account for 60%, friction losses account for 35%, and air drag accounts for 5%.

Table 2  Share rate for 0% slope, increasing rate for 5% slope, contribution rate and reduction rate of Car 2020, and methods for reduction (Source: Reference [1,3])

<table>
<thead>
<tr>
<th>Component</th>
<th>Element</th>
<th>Share rate on 0% slope, %</th>
<th>Increasing rate on 5% slope, %</th>
<th>Contribution rate of Car 2020, %</th>
<th>Reduction rate of Car 2020, %</th>
<th>Methods for reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Oil pump</td>
<td>2.4</td>
<td>86</td>
<td>4.7</td>
<td>17</td>
<td>Low viscosity Oil (LVO)</td>
</tr>
<tr>
<td>Crankshaft bearings</td>
<td>2.6</td>
<td>96</td>
<td>5.3</td>
<td>50</td>
<td>Narrow BRG, Texture, Surface treatment, LVO</td>
<td></td>
</tr>
<tr>
<td>Pistons and piston rings</td>
<td>2.8</td>
<td>180</td>
<td>7.2</td>
<td>71</td>
<td>Narrow piston skirt and small h1 of ring, Low piston ring tension, Surface treatment</td>
<td></td>
</tr>
<tr>
<td>Valve system</td>
<td>0.8</td>
<td>180</td>
<td>2.0</td>
<td>75</td>
<td>Surface treatment, Roller follower, Stem-seal improvement</td>
<td></td>
</tr>
<tr>
<td>Chain/Belt</td>
<td>2.4</td>
<td>180</td>
<td>6.2</td>
<td>50</td>
<td>Guide material, Smooth link, Narrow width</td>
<td></td>
</tr>
<tr>
<td>Pumping loss</td>
<td>7.0</td>
<td>-7</td>
<td>9.9</td>
<td>29</td>
<td>Exhaust gas recirculation, Miller cycle</td>
<td></td>
</tr>
<tr>
<td>Water pump</td>
<td>2.0</td>
<td>87</td>
<td>4.0</td>
<td>25</td>
<td>Seal improvement, Electric drive</td>
<td></td>
</tr>
<tr>
<td>Transmission/Final drive gears</td>
<td>0.1</td>
<td>43</td>
<td>0.3</td>
<td>50</td>
<td>Downsize, LVO, Ball bearing</td>
<td></td>
</tr>
<tr>
<td>Gears</td>
<td>1.4</td>
<td>200</td>
<td>5.6</td>
<td>50</td>
<td>High accuracy, LVO</td>
<td></td>
</tr>
<tr>
<td>Final drive gears</td>
<td>0.5</td>
<td>100</td>
<td>1.5</td>
<td>50</td>
<td>High accuracy, LVO</td>
<td></td>
</tr>
<tr>
<td>Clutches</td>
<td>1.25</td>
<td>87</td>
<td>3.9</td>
<td>20</td>
<td>LVO</td>
<td></td>
</tr>
<tr>
<td>Oil pump</td>
<td>1.75</td>
<td>87</td>
<td>5.1</td>
<td>14</td>
<td>LVO</td>
<td></td>
</tr>
<tr>
<td>Wheels</td>
<td>Brakes (Drag force)</td>
<td>1.2</td>
<td>0</td>
<td>2.5</td>
<td>92</td>
<td>Noncontact</td>
</tr>
<tr>
<td>Hub bearings</td>
<td>1.3</td>
<td>5</td>
<td>2.7</td>
<td>62</td>
<td>Seal improvement, Grease</td>
<td></td>
</tr>
<tr>
<td>Tires</td>
<td>7.5</td>
<td>10</td>
<td>16.1</td>
<td>35</td>
<td>Material molecular design, Tread, High pres.</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 Breakdown of passenger-car energy consumption for constant velocity running at 60 km/h on 0% slope road (Source: Reference [1])
of the total fuel consumption. The study group members who are also members of automobile manufacturers and car-parts manufacturers have proposed reduction rates of friction losses for the car manufactured in 2020 (Car 2020) elements, and these are listed in Table 2 with the corresponding reduction methods. Only the reduction rate of the brake loss (drag force in running) was proposed by the author, because the study group lacked a brake manufacturer in the member of study group. The author thus conducted a study on the “Development of Disk Brake without Drag Force” with the help of Grants-in-aid for Scientific Research 15k13857 (2015). The results obtained from the aforementioned study will be presented at the Tribology conference 2017 Spring Tokyo, JAST.

The reduction rates of the losses due to the various car elements from 2010 to 2020 could be proposed based on the experience of the members. This study, however, cannot be completed only with this achievement because the title of this study demands the prediction of fuel savings realized by the reduction of friction losses.

3.2 Reduction of tire rolling resistance and contribution rate

The Japan Automobile Tyre Manufacturers Association’s estimates of the contribution rate of the reduction in the tire rolling resistance to fuel savings [4] are shown in Table 3. If the contribution rate of the tire is 10%, the fuel consumption is reduced by 2% when the tire rolling resistance is reduce by 20% (0.1 × 0.2 = 0.02). In the case of a constant speed as shown in Table 3, the value of the contribution rate ranges from 20 to 25%.

Table 3 Contribution rate of tire proposed by Japan Automobile Tyre Manufacturers Association (Source: Reference [4])

<table>
<thead>
<tr>
<th>Driving conditions</th>
<th>Tire contribution to fuel consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant speed</td>
<td>20–25 %</td>
</tr>
<tr>
<td>Mode driving</td>
<td>10–20 %</td>
</tr>
<tr>
<td>Actual city driving</td>
<td>7–10 %</td>
</tr>
</tbody>
</table>

value of 20% is the contribution rate when a car drives at a constant velocity of 110 km/h [5] and the air drag accounts for a large percentage of the running resistance. The contribution rate of 25% is suitable for a constant velocity of 60 km/h. As shown in Table 2, the share percentage of the fuel consumption due to the tire is 7.5% for a constant velocity of 60 km/h. The large difference between the values of 7.5% and 25% suggests the existence of a mechanism that can explain the tire contribution rate of 25%.

3.3 Holmberg report

Early in 2012, Holmberg et al. reported the fuel consumption of cars all over the world [2]. They analyzed the fuel consumption for an average velocity of 60 km/h and derived the following conclusions regarding the fuel savings:

1. One-third of the fuel energy is used to overcome friction in the engine, transmission, tires, and brakes.
2. Reductions in the frictional losses (including air drag) will have a threefold improvement on the fuel economy, as it will reduce both the exhaust and cooling losses in the same ratio.
3. In practical use, for an average velocity of 60 km/h, the fuel consumption of Car 2020 can be reduced by 52% as compared with Car 2010.

Holmberg et al. analyzed the fuel consumption for an average velocity of 60 km/h for city driving and highway driving. Conclusion (1) shows almost the same share percentage of the total friction loss as that obtained by the study group. Conclusion (2) is remarkable, in that it states that the reductions in the frictional losses decrease the exhaust and cooling losses in the same ratio (threefold improvement). Although engine specialists do not agree with the threefold improvement, it can be acceptable as a maximum estimation if the engine efficiency remains almost unchanged with the decrease in the friction losses. Now, the threefold improvement will be applied to the example of tire rolling loss. As the total friction loss is 40%, as shown in Fig. 1, the share of the tire loss in the total friction loss is 18.75% (7.5 × 40 = 0.1875). If the tire loss is eliminated, the reduction rate of the fuel consumption is 18.75% because the exhaust and cooling

![Fig. 2 Fuel-savings realized by reducing only tire loss by 10% in constant velocity running on a 0%-slope road (with retroactive effect) (Source: Reference [1,3])](image-url)
losses are reduced in the same ratio. Nevertheless, this reduction rate, which is a maximum estimation, is still less than the contribution rate of 25% given by the Japan Automobile Tyre Manufacturers Association.

3.4 Retroactive effect
When the tire rolling loss was reduced, it was assumed that the other elements keep the friction losses until the last session. The oil pump loss and clutch loss do not change unless the engine speed changes. However, in the case of gears or bearings, the motive power that is transmitted by these elements decreases if the tire rolling loss is reduced, and thus, the friction losses of these elements decrease. Therefore, as shown in Fig. 2, the final fuel consumption is calculated with decreased friction losses of the affected elements when the tire rolling loss is reduced by 10%.
The calculated result shows that the fuel consumption is reduced by 2.77%, and this means that the contribution rate of the tire is 27.7%. It can be said that the value of 27.7% agreed well with the value of 25% given by the Japan Automobile Tyre Manufacturers Association, because the aforementioned calculation is a maximum estimation. The influence of the downstream-element-loss reduction on the upstream-element loss is called the retroactive effect.

4 Approximation model for practical use

In the past, the fuel consumption of passenger cars was measured for the running mode with a constant velocity of 60 km/h. However, the values thus obtained were very different from those obtained during the practical use of cars. Nowadays, a mode traveling fuel consumption following a specific mode traveling procedure (JC08 in Japan) is used to obtain the fuel efficiency index. A reduction in the fuel consumption of 35% from 2010 to 2020 was calculated for running at a constant velocity of 60 km/h. However, the requirement for estimating the fuel efficiency during practical use still exists. It is difficult to estimate the fuel consumption in JC08-mode traveling because it includes cold-start, complex speed, and traffic information. Consequently, a traveling pattern for which the fuel consumption can be calculated easily is proposed. This method will be called approximate practical running.

4.1 Traveling pattern of approximate practical running

Passenger cars consume a large volume of fuel during acceleration and climbing. The climb is substituted for the acceleration, because it is difficult to estimate the fuel consumption during acceleration for a case in which the engine speed changes incessantly. Therefore, it is decided that the traveling pattern of approximate practical running should consist of 30% climbing on a 5% slope, 40% running on a 0% slope, and 30% descending on a 5% slope over a total distance of 100 km at constant velocity of 60 km/h. Here, the climb is defined as the climbing of a 5%-slope road at a constant velocity of 60 km/h. The value of 5% considered is the maximum slope of an arterial road without a climbing lane for slower traffic in Japan. When the car descends the 5%-slope road, the running speed increases even if the accelerator pedal is released.

4.2 Increase in fuel consumption during climbing

Not only an overcoming potential energy but also the increases in the element losses add to the fuel consumption during the climbing of a 5%-slope road. The increasing rates of the element losses are listed in Table 2. The increase in the engine speed from 1,500 to 2,800 rpm directly affects the increases in the friction losses of the engine elements. These results are shown graphically in Fig. 3. The pure climbing potential energy is calculated using the low calorific power of gasoline—32.9 MJ/L. The exhaust and cooling losses are one and half times as much as the fuel consumption of mechanical output 5.38 L/100 km, and the total fuel consumption obtained is 13.45 L/100 km. This value is approximately 3 times that of the fuel consumption for constant velocity running on a 0% slope.

4.3 Contribution rate of element in approximate practical running

The fuel consumption of Car 2010 in approximate practical running can be found to be 13.45 L/100 km during climbing, 5.0 L/100 km for running on a 0% slope, and 0 L/100 km during descending (because fuel cut), which is shown as follows:
(13.45 × 0.3) + (5.0 × 0.4) + (0 × 0.3) = 6.04 (L/100 km).

This fuel consumption value corresponds to 16.6 km/L, and it is reasonable for the fuel consumption during safety driving on a suburban load. The contribution rates of car elements in approximate practical running were calculated. For the calculation, the same method that was used for the calculation of the contribution rate on reducing the tire rolling loss was used. The calculated results are listed in Table 2. The contribution rate of the tire is 16.1%, and this values is in the range of 10-20% during mode driving, as shown in Table 3, as given by the Japan Automobile Tyre Manufacturers Association. This value is smaller than the value of 27.7%, which is obtained for constant velocity running on a 0% slope, because the increasing rate of the tire rolling resistance on the 5% slope shown in Table 2 is relatively smaller than those of the other elements.

It should be noted that the contribution rates in Table 2 are calculated using the share rate of the Car 2010 elements and without the predicted friction loss reduction rates of Car 2020 given in Table 2. In the next chapter, the fuel consumption of Car 2020 in approximate practical running will be calculated by using the friction loss reduction rates of Car 2020 predicted by the study group. Even if you do not agree with the predicted values, you can calculate the fuel consumption of Car 2020 by using friction loss reduction rates that are estimated by you.

5 Fuel Consumption of car 2020 in approximate practical running

The fuel consumption of Car 2020 is calculated by using the predicted friction loss reduction rates while considering the threefold improvement and the retroactive effect. The calculated result shows that the fuel consumption for constant velocity running on a 0% slope is 3.25 L/100 km, which is a 35% reduction from that of Car 2010. The fuel consumption in approximate practical running is 4.30 L/100 km, which is a 29% reduction as compared with the fuel consumption of 6.04 L/100 km of Car 2010. In the case of passenger cars, the target of the Japanese Government for the reduction in the carbon dioxide emissions will be reached using tribology technology in the short term.

6 Contribution rate of car weight and hybrid vehicle

The car weight is taken in consideration when the fuel consumption is calculated in approximate practical running. The reduction of the fuel consumption is estimated by decreasing the car weight, and the calculated result shows that the contribution rate of the car weight is 55.8% [6]. In the same way, the contribution rate of all elements in the power train, which account for 35% of the fuel consumption, can be calculated by reducing all the element losses in the same ratio. Although the contribution rate is slightly decreased as the reduction rate of the element loss is increased, the value of all the elements is 71% when the reduction rate is 50%. This shows that the friction loss reduction is more effective for the fuel consumption as compared with the car weight reduction.

Various discussions have focused on the future prospects of hybrid electric vehicle (HEV), which is a typical eco-friendly car in Japan. The study group calculated the reduction in the fuel consumption of the HEV by taking advantage of tribology and formulating bold hypotheses [3]. The result showed a 32% reduction in the fuel consumption of an HEV manufactured in 2020 (HEV 2020) as compared to that manufactured in 2010 (HEV 2010), as shown in Fig. 4. If the result is compared with that of the conventional Car 2010, it is found that the fuel consumption of HEV 2020 is lower by 28%, whereas the fuel consumption of HEV 2010 is lower by 25% as compared to the conventional Car 2010, as shown in Fig. 4. This means that the difference in fuel consumption between an HEV and a conventional car will increase in the future.

7 Conclusions

Vehicles including freight cars have not been working, just transporting cargoes in a horizontal plane in the long run. The fuel is consumed primarily to overcome the friction loss and air drag. Therefore, a reduction in the friction losses would effectively decrease the fuel consumption. The reduction of friction in an HEV improves its fuel efficiency more effectively than in the case of a conventional car because, in an HEV, the kinetic energy is recovered during braking and used during acceleration and climbing, and thus, only the friction losses remain. The conclusions of this expository writing are as follows:

1. It is possible to estimate the effect of friction loss reduction on the improvement of the fuel efficiency of passenger cars by taking the threefold improvement and the retroactive effect into consideration.

2. The fuel consumption in approximate practical running that is close to actual use can be predicted. Approximate practical running consists of 30% climbing on a 5% slope, 40% running on a 0% slope, and 30% descending on a 5% slope with a car at a constant velocity of 60 km/h. The contribution rates of the car elements can be proposed for Car 2010 based on approximate practical running.

3. The fuel consumption of Car 2020 is decreased by 29% as compared to Car 2010 with the friction loss reductions that are proposed by the study group.

4. Although the contribution rate is slightly decreased as the reduction rate or friction loss is increased, the value of all the elements without considering the air drag force is 71% when the reduction rate is 50%. This shows that friction loss reduction is more effective for reducing the fuel consumption as compared to the car weight reduction.

5. Comparing with that of a conventional car, it is found that the fuel consumption of HEV 2020 is lower by 28%, whereas the fuel consumption of HEV 2010 is lower by 25%. This means that the difference in fuel consumption between an HEV and a conventional car will increase in the future.
The vehicle is a very useful tool that has made the importance of tribology for developing global warming mitigation measures known to society. Automobile manufacturers and car-parts manufacturers have endeavored to decrease friction losses in automobiles, but there are few discussions regarding the effects of friction loss reduction on the overall power train system. Good proposals based on references from this expository writing are expected to invigorate the JAST.


References