Fuel Economy Improvement of an Electric All Wheel Drive System (e-AWD)

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Abstract

e-AWD(electric All Wheel Drive) system can be defined as hybrid vehicle which has an electric motor driving unit in the rear portion and a hybrid system in the front portion. Since this system needs an additional driving unit in the rear, fuel economy decrease can be happened. To prevent this decrease, it needs to study to find fuel economy improvement method of the e-AWD System. This paper introduces this method in the certification cycle (EPA-FTP, HWY) and the real road condition.

First, in certification cycle, we found the method by optimizing the power distribution between the front and rear wheels. With increment of driveline efficiency in EV, HEV-Assist, Regenerative mode, fuel economy of e-AWD was improved as much as 2WD hybrid system.

Second, in the real road, we found the method by changing the control techniques (In this paper, the real road condition was defined as ‘low SOC and low speed driving’). Since state of charge is very low in this condition, the use of battery is limited and engine power drives the vehicle alone. In the case of 2WD hybrid system, engine power is delivered to wheels by engine clutch slipping which causes decrease of driveline efficiency. But e-AWD system can engage the engine clutch and conduct series driving by using front and rear motor. About 3% of fuel economy was improved by changing in such control method.

Keywords: e-AWD HEV, Fuel Economy, FTP cycle, HWY cycle, Rear motor, Power distribution

1 Introduction

E-AWD hybrid system can be defined as a system has hybrid system in front, motor driving system in rear. As an example, RX450h and Highlander hybrid of Toyota have THS system in front, motor driving system in rear. Advantage of this system is high fuel economy (compared to gasoline 4WD vehicles) and AWD performance (on snow road, Off-road, etc.). However, weight increase due to adding rear motor driving unit can produce a result of decrease of fuel consumption.

In this study, we look at the characteristic behaviour of e-AWD hybrid system and research the method improving fuel economy.

2 E-AWD System

2.1 Definition of the e-AWD System

E-AWD system of this study is shown in the fig.1. Internal combustion engine and front electric motor drive the front wheels and rear electric
motor drive rear wheels. The front motor and engine clutch are installed between the engine and the transmission. (It’s called parallel hybrid system) The rear driving unit is mechanically separated from the front system.

![Diagram of E-AWD hybrid system](image)

**Figure 1: E-AWD hybrid system**

### 2.2 System characteristics

Parallel hybrid system usually has four driving mode (EV mode, Hybrid Assist/Charge mode, Regenerative braking mode). Because rear wheel driving system can move independently, e-AWD hybrid system has a characteristic behavior in each mode compared to 2WD hybrid system. That’s point of improvement of fuel economy. Fig.2 shows possibilities of improvement of driving efficiency in EV, HEV Assist and regenerative braking mode. Fuel economy could be better when required power is distributed to rear motor optimally.

![System Configuration Table](image)

**Figure 2: System Configuration**

### 3 Improvement of fuel economy in EPA Certification (FTP/HWY) cycle

Simulation had been conducted by ECMS method in FTP and HWY cycle. Gear stage and SOC level had been constructed properly.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>2WD HEV</th>
<th>e-AWD HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV</td>
<td>Front motor driving</td>
<td>Front or Rear motor driving</td>
</tr>
<tr>
<td>HEV Assist/Charge</td>
<td>Front motor assisting</td>
<td>Front or Rear motor assisting</td>
</tr>
<tr>
<td>Regenerative Braking</td>
<td>Front motor generating</td>
<td>Front or Rear motor generating</td>
</tr>
</tbody>
</table>

**Figure 3: FTP(Top), HWY(Bottom) cycle**

#### 3.1 EV mode

EV mode is that electric motor drive the vehicle by using electric energy. 2WD hybrid system is use only front motor, but e-AWD hybrid system can use front and rear motor optionally.

![EV mode diagram](image)

**Figure 4: EV mode**

In case of e-AWD HEV system, driving efficiency of electric motor was improved FTP 0.3%, HWY 0.1% by using rear motor.

<table>
<thead>
<tr>
<th>EV mode</th>
<th>e-AWD HEV</th>
<th>2WD HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FTP</td>
<td>HWY</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Frontmotor -0.4% +0.1% base base</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frontmotor -+1.3% +0.3% - -</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rearmotor -0.3% +0.1% Base base</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1: EV mode motor efficiency**

![Motor operating point example](image)

**Figure 5: motor operating point example in EV mode**
In low speed area, driving efficiency of e-AWD hybrid was improved 0.4% by Power distribution to the rear wheels. In mid speed area, improved 0.7% by change driving motor from front to rear. There wasn’t efficiency improvement above 60kph. Because rear motor efficiency decline rapidly above that speed.

### 3.2 HEV mode

#### 3.2.1 HEV-Assist mode

In assist mode, electric motor drives the vehicle with engine. Like EV mode, e-AWD hybrid system can use front and rear motor optionally.

![Figure 6: HEV – Assist mode](image)

Table 2: HEV - Assist mode motor efficiency

<table>
<thead>
<tr>
<th>HEV-Assist mode</th>
<th>e-AWD HEV</th>
<th>2WD HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FTP</td>
<td>HWY</td>
</tr>
<tr>
<td>Front motor</td>
<td>-1.2%</td>
<td>-0.4%</td>
</tr>
<tr>
<td>Rear motor</td>
<td>+1.3%</td>
<td>+2.3%</td>
</tr>
<tr>
<td>Front + Rear</td>
<td>+0.6%</td>
<td>+0.2%</td>
</tr>
</tbody>
</table>

In same manner as EV mode, electric motor driving efficiency was improved FTP 0.6%, HWY 0.2%.

#### 3.2.2 HEV-Charge mode

In HEV-Charge mode, extra power of the engine charges the battery through electric motor. E-AWD hybrid system can use rear motor to charge, but the power path of rear motor is disadvantageous as compared with front motor.

![Figure 7: HEV – Charge mode](image)

Table 3: HEV - Charge mode motor efficiency

<table>
<thead>
<tr>
<th>HEV-Charge mode</th>
<th>e-AWD HEV</th>
<th>2WD HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FTP</td>
<td>HWY</td>
</tr>
<tr>
<td>Front motor</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
<tr>
<td>Rear motor</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Front + Rear</td>
<td>±0.0%</td>
<td>±0.0%</td>
</tr>
</tbody>
</table>

Accordingly, 2WD HEV and e-AWD HEV system use front motor to charge battery. Electric motor driving efficiency was not improved.

### 3.3 Regenerative braking mode

When the driver is putting on the brakes, the braking energy charges the battery through electric motor in regenerative braking mode.

![Figure 8: Regenerative braking mode](image)

Table 4: Regenerative braking mode motor efficiency

<table>
<thead>
<tr>
<th>Regenerative braking mode</th>
<th>e-AWD HEV</th>
<th>2WD HEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FTP</td>
<td>HWY</td>
</tr>
<tr>
<td>Front motor</td>
<td>+3.0%</td>
<td>+5.8%</td>
</tr>
<tr>
<td>Rear motor</td>
<td>+5.4%</td>
<td>+8.5%</td>
</tr>
<tr>
<td>Front + Rear</td>
<td>+4.9%</td>
<td>+7.7%</td>
</tr>
</tbody>
</table>

Generating efficiency of electric motor is improved FTP 4.9%, HWY 7.7% by distributing of regenerative braking energy to rear motor. In this mode, the efficiency enhancement of electric motor is better than other mode. Because Regenerative braking operation point of electric motor is on high torque area. (motor efficiency decline rapidly in high torque area.)
Fig. 9 shows the example of motor operating point in Regenerative braking mode. Generating efficiency of e-AWD hybrid was improved 3.5% in first example by distribution of regenerating power to rear motor. In second example, 16.0% of efficiency improvement occurred because rear motor regenerated the portion that could not be due to limit of front motor torque.

Fig. 10 and Fig. 11 show motor operation point of FTP, HWY mode. Blue dot is driving point, red dot is generation point. As you see, motor efficiency of E-AWD hybrid system is improved by power distribution to rear motor.

### 3.4 Fuel economy of FTP, HWY cycle

Fuel economy of e-AWD hybrid is decreased FTP 2.0%, HWY 1.2% by weight growth. But through the use of the rear motor optimally, driving efficiency is improved, and then fuel economy is increased as much as 2WD hybrid system.

### 4 Improvement of fuel economy in real load

Because 2WD parallel hybrid system have clutch between engine and motor, it can pure EV driving, HEV assist driving when needs high power. But in low speed and low SOC state, vehicle use only engine power though clutch slipping. Decrease of driving efficiency and durability is occurred.

Table 5 shows estimated driving state which based on real road.

<table>
<thead>
<tr>
<th>Index</th>
<th>Driving state</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>An uphill road</td>
<td>8–16% (real road)</td>
</tr>
<tr>
<td>Speed</td>
<td>Low</td>
<td>congested area</td>
</tr>
<tr>
<td>SOC Level</td>
<td>Low</td>
<td>less than 30%</td>
</tr>
<tr>
<td>A/C</td>
<td>ON</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 shows estimated driving state which based on real road.

Fig. 13: 2WD hybrid system power flow

Engine power is transmitted to the vehicle through the clutch slipping in 2WD hybrid system. Power loss and aggravation of durability of clutch is occurred.
4.1 Toyota hybrid system behaviour

In low speed and low SOC, Toyota hybrid system use Series-parallel and EV drive. Even when the battery is discharged electric motor drives the vehicle through generator. Because engine operate freely regardless of vehicle speed, it is possible to operate optimally.

4.2 Propose control method of e-AWD hybrid system

Based on Toyota system, e-AWD hybrid system can use the front motor as MG1 of Toyota hybrid system.

Fig.15 is Series drive. Front motor generate electricity from engine power, rear motor is drive the vehicle.

Fig.16 is Series-Charge and EV drive. Front motor generate and rear motor drive as fig.15, extra power charge the battery. When the SOC is up to a certain level, rear motor drive the vehicle by using battery energy only.

Clutch Slip loss is disappeared by those control, but driving efficiency of fig.15 get worse. Operation of engine is limited to vehicle load and efficiency of rear motor isn’t good. On the other hand, engine of fig.16 can operate freely and optimally, thus engine efficiency of fig.16 is increased 10%. Although efficiency of rear motor is not good, total driving efficiency is improved.

Fuel economy improvement of e-AWD hybrid system is possible by using rear motor in EPA certification cycle and real load. Details are below.

- Fuel economy of e-AWD hybrid system could be decreased by weight growth. It caused by adding rear driving system.
- But Optimized power distribution of front and rear motor improve driving efficiency in FTP/HWY cycle.
- The biggest improvement is occurred in regenerative braking mode through changing operation point from high torque area to low torque area by using rear motor.
- Above high speed (about 60kph), rear motor isn’t useful because rear motor efficiency decline rapidly.
- In low speed and low SOC driving, there is fuel economy improvement if it uses Series-charge and EV control method instead of clutch slip driving.

Acknowledgments

Fuel economy of fig.16 is better about 3.7% than clutch slip driving.
References


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