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Efficiency Enhancement of a New Two-Motor Hybrid System

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Abstract

A new two-motor hybrid system is developed to maximize powertrain efficiency. Efficiency of the system is drastically enhanced without any driving performance sacrifices by switching driving modes from "Hybrid Drive" to "EV (Electric vehicle) Drive" or "Engine Drive" according to the driving condition, along with the application of a series hybrid based system to make full use of high flexibility of engine operating points. Basic concepts of the maximization of powertrain efficiency including an applied system configuration and control technologies are discussed in this paper.

Along with this system, a high capacity Li-ion battery and an on-board charger are installed in 2014 Honda Accord Plug-In to add practical plug-in HEV capabilities. Superior fuel economy is achieved with values of 46 MPG (Miles Per Gallon) in CS (Charge Sustaining) mode, 115 MPGe (Miles Per Gallon equivalent) in CD (Charge Depleting) mode and 13miles of AER (All Electric Range). MPGe is a unit of fuel economy for the alternate fuel vehicles such as plug-in hybrid electric vehicles or electric vehicles. The ratings are calculated by converting used electric energy into equivalent amount of gasoline.

Keywords: Two-motor Hybrid, Series Hybrid, Parallel Hybrid, Series-Parallel Hybrid, Plug-in Hybrid,

1 Introduction

Approximately one-fourth of total CO₂ emission which is considered the main cause of global warming is emitted from the transportation sector. Accordingly, compliance with global strengthening of emission regulations to reduce it is an urgent issue for the automobile industry.

Although individual auto manufacturers are developing ZEV (Zero Emission Vehicle) such as FCEV (Fuel Cell Electric Vehicle) or BEV (Battery Electric Vehicle) as a final solution, realization of a full-scale popularization is expected to need several decades due to current

technical limitations such as limited driving range, lack of infrastructures and higher cost.

Therefore, fuel efficiency enhancement of HEVs (Hybrid Electric Vehicles) is one of the most effective and practical countermeasures to reduce CO₂ emission, since its application is expanded globally in recent years.

To answer these situations, a new two-motor hybrid system is developed to maximize powertrain efficiency. Details of applied new control technologies are discussed in this paper.

2 Background

Basic system configurations and features of existing hybrid systems are explained in this

chapter as background information for the study of a new system. Hybrid systems for automobile application which is already on the market can be classified into the following three types.

2.1 Series Hybrid Electric Vehicle

A series hybrid electric vehicle has an engine and a generator for electric power generation and stores up generated electric energy into an energy storage device such as a battery or a capacitor. Then the vehicle is propelled by a traction motor driven by stored electric energy. (Figure 1)

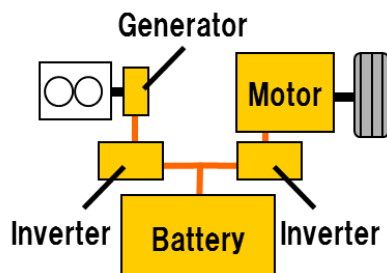


Figure 1: Series hybrid electric vehicle

Since all engine output is converted to electric energy during the process of power transmission to the driveshaft, electric transmission ratio of this system is 100%. An advantage of this system is that the engine can be constantly operated in highly efficient areas unrelated to the driving condition since there is no physical connection between the engine and the driveshaft. On the other hand, losses during charge and discharge are relatively large because all propulsion energy must be delivered through the energy storage device. Also, this system requires a relatively large energy storage device because whole propulsion power need be guaranteed by its output. Therefore, practical utilization examples of series hybrid electric vehicles tend to be larger vehicles such as busses and commercial vans.

2.2 Parallel Hybrid Electric Vehicle

Since both an engine and a motor are physically connected to a driveshaft, both outputs can be used as propulsion power for parallel hybrid vehicles. Some of them have a switching mechanism of the motor and the engine and some of the rest have a directly connected motor on the drivetrain to perform a motor assist and regeneration. Since whole propulsion power is transferred to the driveshaft through the mechanical path, mechanical transmission ratio of this system is considered as 100%.

Honda IMA (Integrated Motor Assist) system, which is the representative example of parallel hybrid electric vehicles on the market, has an ultra-thin motor between the engine and the transmission. The motor is directly connected to the crankshaft to construct a parallel hybrid configuration. (Figure 2)

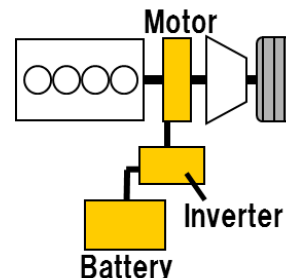


Figure 2: Parallel hybrid electric vehicle (Honda IMA)

2.3 Series-Parallel Hybrid Electric Vehicle

A series-parallel hybrid electric vehicle has two paths for engine output. One is a mechanical transmission path directly connected to a driveshaft and the other is an electric transmission path through a generator. The representative example on the market of this system is Toyota THS (Toyota Hybrid System).

THS has a planetary gear set to divide engine output into two paths. The sun gear is connected to a generator and the ring gear is connected to a driveshaft. In addition to the above configuration, THS constructs both mechanical and electric transmission paths of engine output by installing a traction motor directly connected to the driveshaft. (Figure 3) To improve overall efficiency, power transmission ratio of two paths is adjusted in response to the driving condition by controlling rotational speed of the gear set.

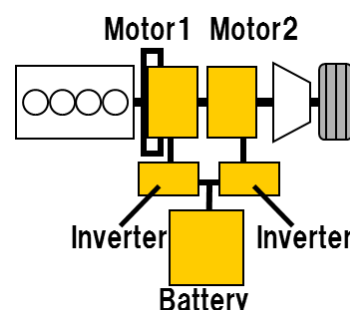


Figure 3: Series-parallel Hybrid (Toyota THS)

3 Basic Concepts

Basic concepts of the maximization of powertrain efficiency which is the target of this study are described in this chapter.

3.1 Optimization of Engine Operating Points

Even if it is a HEV, reduction of fuel consumption during engine activation is predominant to enhance overall efficiency, namely fuel economy, just like a conventional gasoline-powered vehicle. Engine operating points should be kept in the area of lower fuel consumption ratio by utilising the electric transmission path that has higher flexibility of rotational speed.

3.2 Enlargement of Electric Transmission Ratio

As described before, engine output of a conventional series-parallel hybrid electric vehicle is divided into electric and mechanical transmission paths and its power ratio is adjusted in response to the driving condition to enhance overall efficiency. Basic consideration to determine the new system configuration is as follows. If efficiency of a motor, a generator and an inverter exceed a certain level, the higher electric transmission ratio, the higher overall efficiency is realized.

A basic idea of the desired value of electric transmission efficiency is described below. The relationship between the electric transmission efficiency and overall system efficiency of two systems which differ in the rate of electric transmission ratio is shown in Figure 4.

Since the line of System A with higher electric transmission ratio has a steeper inclination due to a higher correlation between two parameters, it will have the intersection with System B, and overall efficiency of System A will exceed System B in the domain where electric transmission efficiency is higher than this intersection.

If System B is a conventional series parallel hybrid system and System A is a developed system, a desired value of the electric transmission efficiency enhancement to realize higher overall efficiency compared with a conventional system should be higher than the intersection.

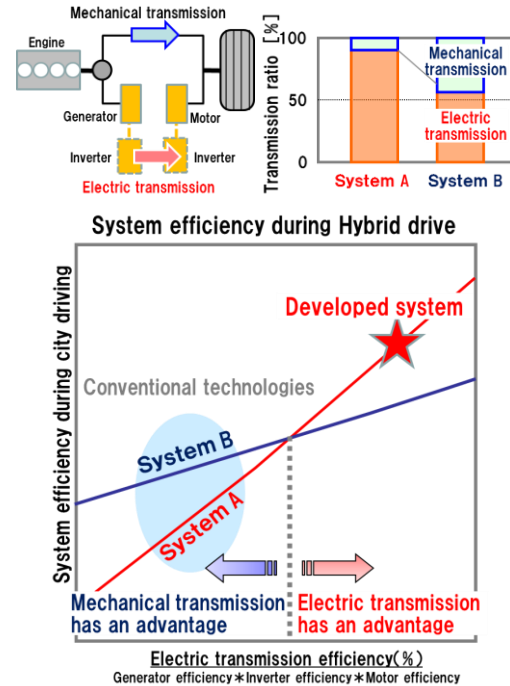


Figure 4: Desired value of electric transmission efficiency

3.3 Application of a Mechanical Transmission Path

If electric transmission efficiency exceeds mechanical transmission efficiency in all domains, a series hybrid electric vehicle whose electric transmission ratio is 100% is the most efficient. However, since the efficiency of an electric powertrain changes in response to the operational conditions such as rotational speed and the required output, it is actually difficult to exceed the mechanical transmission efficiency in all domains. Therefore, overall efficiency will be enhanced by an application of a mechanical transmission path for the engine output in the domain where the efficiency of an electric powertrain is relatively low.

3.4 Optimization of Motor Operating Points

If the vehicle is propelled by utilising an electric transmission path, the driveshaft is directly driven by the traction motor. Therefore, maintaining the operating points of the motor in the domain with higher driving efficiency leads to efficiency enhancement. In other words, the driving efficiency will be enhanced by moving the operating points of the motor to efficient sides using a gearbox or by installing some mechanism to move the efficient domain of the motor operation.

4 System Configuration

4.1 Embodiment of Efficiency Enhancement Concepts

Applied technologies for embodying the four above-mentioned efficiency enhancement concepts are described in this section.

Firstly, a series hybrid based system is applied equipped with a generator directly connected to an engine and a motor directly connected to a driveshaft to construct an electrical transmission path and increase its ratio further.

Next, in order to add a mechanical transmission path, an engine-drive clutch which enables mechanical intermittence of the shafts of the motor and the generator is adopted.

Furthermore, in order to enhance the driving efficiency of the traction motor, a VCU (Voltage Control Unit) which amplifies the battery voltage is adopted. An efficient operating area of the traction motor can be moved according to the driving situation by making the motor operating voltage variable. The details of voltage amplification control are explained in the following chapters.

A block diagram of the powertrain configuration equipped with mentioned conditions is shown in Figure 5, and correlation between four efficiency enhancement concepts and embodiment techniques is shown in Table 1. In Figure 5 Black lines represent mechanical paths and orange lines represent electric paths.

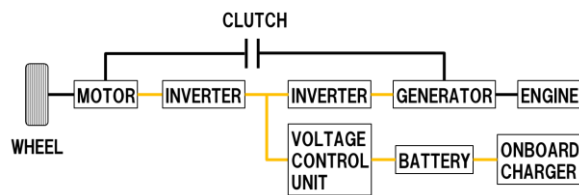


Figure 5: Block diagram of powertrain system

Table 1: Correlation between efficiency enhancement concepts and embodiment techniques

Efficiency enhancement concept	Embodiment technique
Optimization of engine operating points	Applying an electrical transmission path by installing two motors
Enlargement of electric transmission ratio	Applying a series hybrid based system
Mechanical transmission path application	Realization of engine direct drive by utilising a clutch
Optimization of motor operating points	Battery voltage amplification by installing a VCU

4.2 Actual System Configuration

Newly developed devices for the realization of the block diagram shown in Figure 5, and the actual system configuration which is the combination of these devices are explained in this section.

4.2.1 e-CVT

A cross-sectional view of an e-CVT (electric coupled Continuously Variable Transmission) which enables both a series hybrid operation and direct engagement of the engine and the driveshaft is shown in Figure 6.

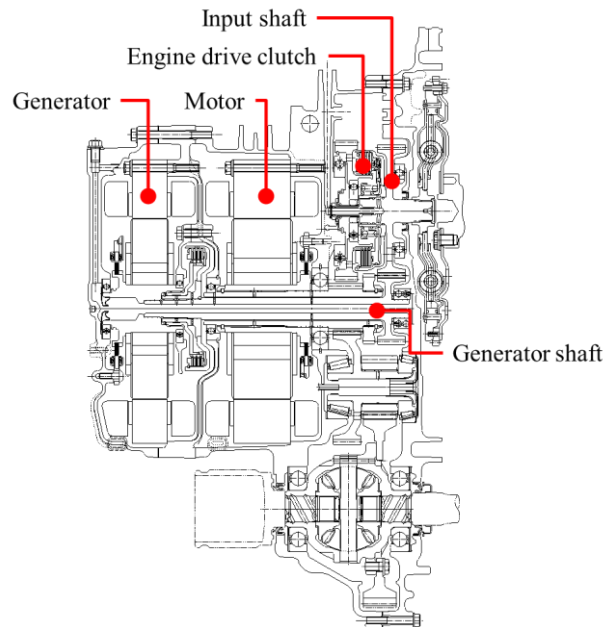


Figure 6: Cross-sectional view of e-CVT

The traction motor directly connected to the driveshaft and the generator directly connected to the engine are integrated into the equivalent size of a conventional transmission and the engine-drive

clutch which combines the motor shaft with the generator shaft is also integrated. Engine power can be directly transferred to the driveshaft by engagement of the clutch. Since mechanical transmission efficiency surpasses electrical transmission only in the domain of a high-speed cruise in actual driving cycles, gear ratio of the engine direct drive is fixed at equivalent of the top gear of a conventional transmission without any shifting.

4.2.2 PCU

Structure of a PCU (Power Control Unit) is shown in Figure 7 and a block diagram is shown in Figure 8. Inverters which convert direct current into alternative current, a VCU which amplifies the battery voltage, ECUs (Electric Control Units) which control a motor and a generator, various sensors and condensers constitute a PCU. Intensive arrangement of these functional parts and water cooling structure make the overall size of the PCU small enough to install in a conventional engine room.

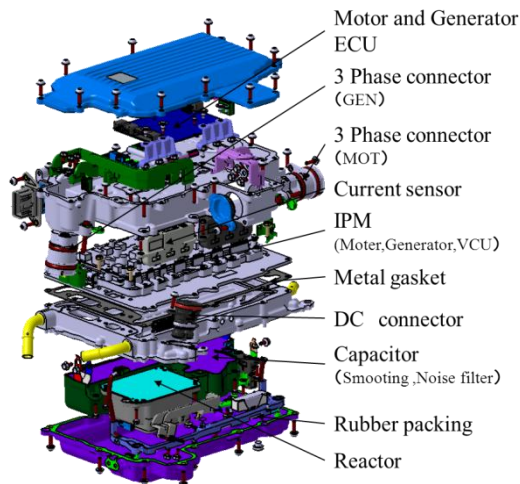


Figure 7: Structure of PCU

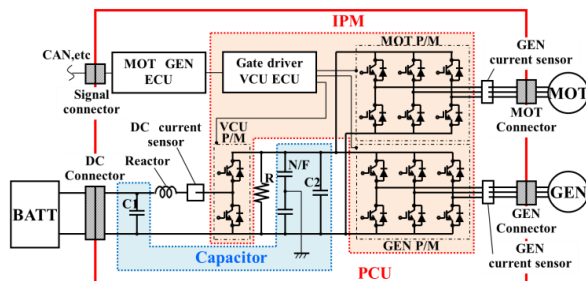


Figure 8: Block diagram of PCU

4.2.3 Overall System Configuration

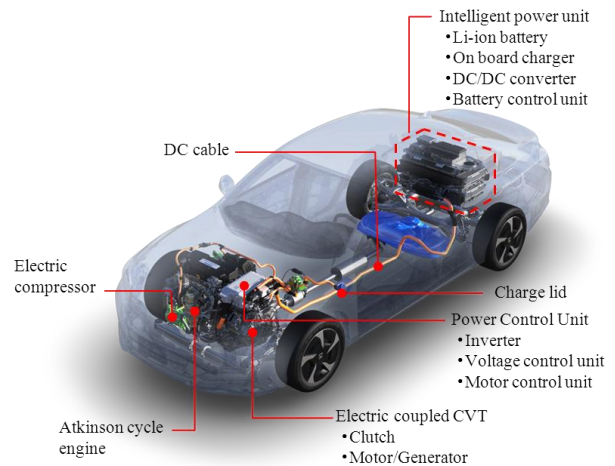


Figure 9: Overall system configuration of 2014 Honda Accord Plug-In

Major components of the powertrain are positioned in the actual vehicle (2014 Honda Accord Plug-In) as shown in Figure 9. The e-CVT is installed in the position of a conventional transmission and utilized in combination with an Atkinson cycle engine optimized for HEV application. The PCU is positioned above the e-CVT and cooled by an independent water cooling circuit separated from the engine's circuit. An IPU (Intelligent Power Unit) is installed behind the rear seats and cooled by cooling fans located in the trunk room. A Li-ion battery specially designed for plug-in hybrid application, a DC/DC converter, a high-power on-board charger and a battery ECU constitute the IPU as one package.

5 Basic Concepts of System Control

5.1 Operation Mode Transition

Power flow in the e-CVT is shown in Figure 10 and operation modes of this system are explained in Table 2.

This system can be operated in three operation modes explained below.

In "EV Drive", the traction motor physically connected to the driveshaft propels the vehicle by using electric energy stored in the battery.

In "Hybrid Drive", the traction motor is driven by electric energy generated by the generator using engine output. The battery behaves as a passive device to provide lack of engine output or be charged by surplus energy.

In "Engine Drive", the engine-drive clutch located between the engine and the wheels is engaged, and

the vehicle is directly propelled by engine output. Fuel efficiency of all driving conditions is maximized by switching these three driving modes properly.

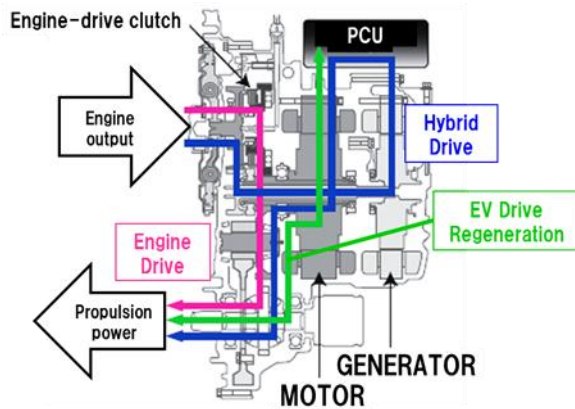


Figure 10: Power flow of e-CVT

Table 2: Operation mode

			— Electric transmission path	— Mechanical transmission path
EV Drive	Hybrid Drive	Engine Drive		
Use electric energy stored in the battery to drive the motor	Use electric energy generated by the engine to drive the motor, with assistance or charging of the battery	Use engine output to directly drive the wheels		

An outline of mode transition in a typical driving cycle is shown in Figure 11. During low-load situation such as launching or city driving, "EV Drive" is mainly selected. Then, the driving mode is switched to "Hybrid Drive" for the acceleration during normal-load or heavy-load situation.

If the vehicle is cruising, intermittent operation between "EV Drive" and "Hybrid Drive" or

"Engine Drive" is selected. In this case, the high voltage battery is charged during engine activation of "Hybrid Drive" and "Engine Drive". Then, stored electric energy is used in "EV Drive" afterwards. Detailed control strategies of intermittent operation are explained in the next chapter.

Fundamentally, operating mode is determined based on efficiency. The basic idea of mode transition is explained below, taking the case of "Engine Drive" and "Hybrid Drive". Comparison of fuel consumption of "Hybrid Drive" and "Engine Drive" is shown in Figure 12. A black line in Figure 12 represents the road load during driving on a flat road.

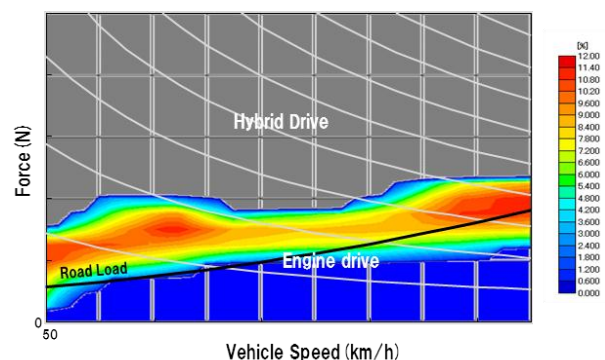


Figure 12: Comparison of fuel consumption of "Hybrid Drive" and "Engine Drive"

"Engine Drive" has superior fuel economy compared with "Hybrid Drive" in red areas, and both driving modes have similar efficiency in blue areas. This diagram represents that the efficiency of "Engine Drive" is better than "Hybrid Drive" in the areas of cruise and slight acceleration. Based on this relationship, "Hybrid Drive" and "Engine Drive" are switched.

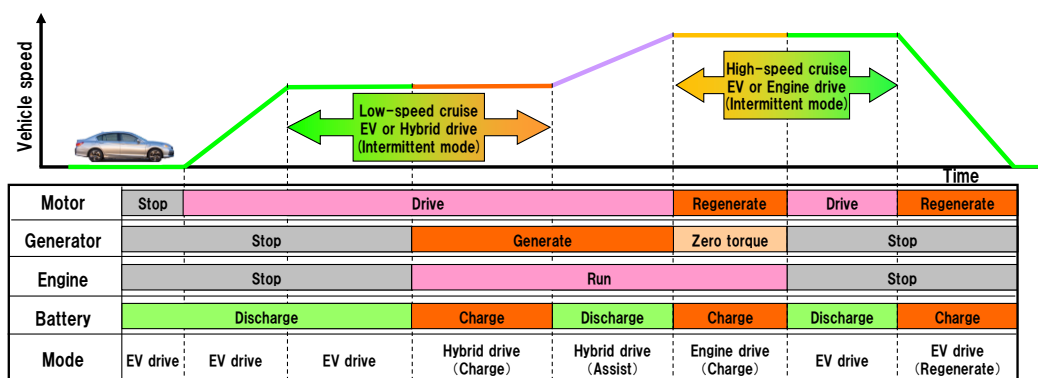


Figure 11: Driving mode transition of typical driving cycle

5.2 Plug-In Hybrid Operation

Figure 13 shows an outline of plug-in hybrid operation.

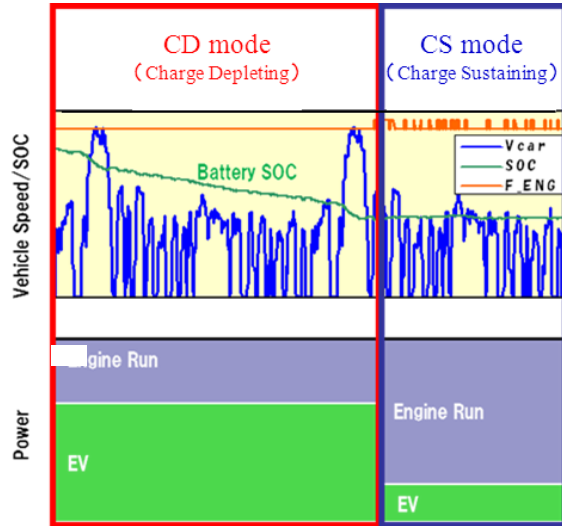


Figure 13: Plug-in hybrid operation

If the battery is fully charged via plug-in charge, a CD (Charge Depleting) mode is selected and the vehicle is propelled by utilizing stored electric energy. Since EV capability is determined by the specification of the high voltage battery, it is fixed by considering following targets.

- Whole of city driving should be covered by "EV Drive".
- EV range should be over 10 miles.

If the battery SOC (State Of Charge) drops to a predetermined level, a CS (Charge Sustaining) mode is automatically selected as shown in Figure 13.

Figure 14 and 15 show operation areas of three driving modes. Fig. 14 represents "CS mode", and Fig. 15 represents "CD mode". A major point of difference between both modes is "EV Drive" area.

It is enlarged in a CD mode to cover whole city driving. Except enlargement of "EV Drive", "Hybrid Drive" and "Engine Drive" are switched just like in a CS mode.

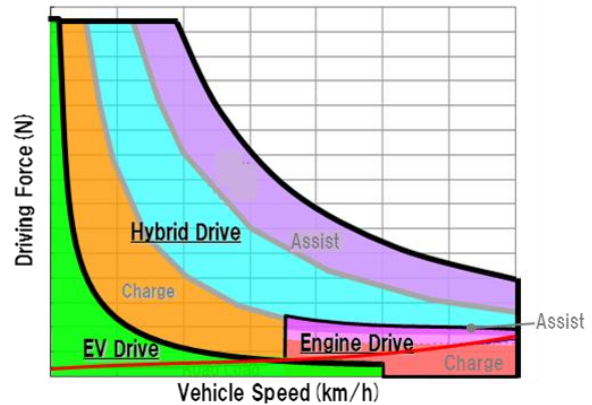


Figure 14: Operation areas of three driving modes (Charge Sustaining mode)

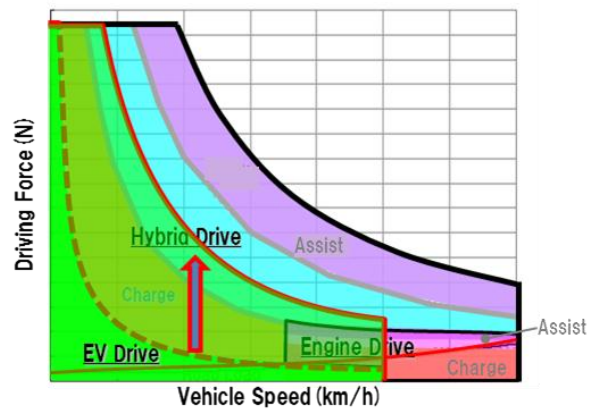


Figure 15: Operation areas of three driving modes (Charge Depleting mode)

6 System Control for Efficiency Enhancement

While this system changes three driving modes according to the driving condition as described before, the control technologies for further efficiency enhancement are introduced in each driving mode.

6.1 Adjustment of Engine Operating Points

Since thermal efficiency of the engine is predominant to overall powertrain efficiency, the key to enhance overall fuel economy is highly efficient operation of the engine.

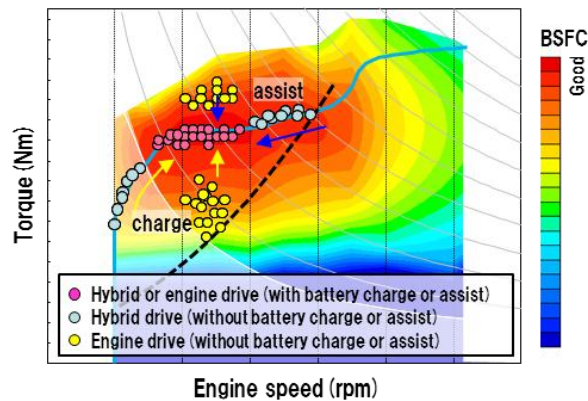


Figure 16: Engine operating point

Figure 16 shows an outline of engine operating points. Red areas represent higher efficiency and blue areas mean relatively low efficiency. The blue line represents the bottom of BSFC (Brake Specific Fuel Consumption)

The engine is activated in "Hybrid Drive" and "Engine Drive" with this system.

In "Hybrid Drive", there is no restriction regarding rotational speeds of the wheels and the engine, since they have no physical connection each other. Therefore, the engine speed can be determined arbitrarily without any relationship with the vehicle speed. If the relationship between input (engine speed) and output (motor speed) shafts of the e-CVT is considered, its operation can be regarded just like a conventional CVT.

The engine operating point (speed and torque) is determined to follow the minimum BSFC for every possible power demand. Moreover, the engine load is increased or decreased by charging or discharging the high voltage battery in order to move engine operating points toward the higher efficiency domain on the minimum BSFC line.

In "Engine Drive", the engine speed is uniquely fixed if the vehicle speed is determined since the engine is physically connected to the wheels via fixed gear ratio. The relationship between engine speed and torque during cruise on a flat road is shown as a black broken line in Figure 16.

Since engine operating points are separated from the minimum BSFC line in response to the driving situation, the engine load adjustment by charging or discharging the high voltage battery is performed also in this mode to fix engine operating points in highly efficient areas.

6.2 Intermittent Operation

During cruising, intermittent operation between "EV Drive" and "Hybrid Drive" or "Engine Drive" is adopted.

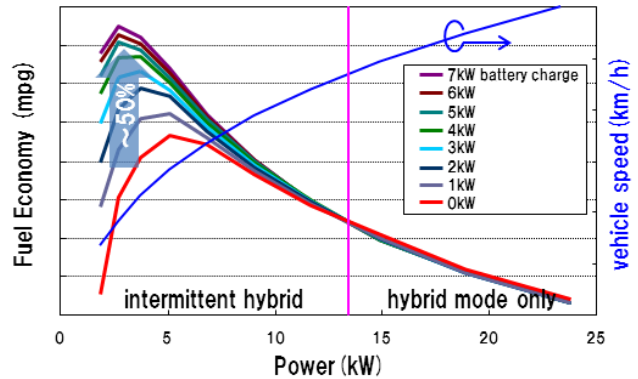


Figure 17: Fuel economy enhancement of intermittent operation

Figure 17 shows fuel economy enhancement by intermittent operation between "EV Drive" and "Hybrid Drive". If required driving power is lower than 15 kW, fuel economy is enhanced up to 50% compared with continuous "Hybrid Drive" (the red line in Figure 17) by applying intermittent operation which means the high voltage battery is charged during "Hybrid Drive" and stored electric energy is used in "EV Drive" afterwards. On the other hand, fuel economy enhancement effect is reduced or gets worse, if required driving power is over 15 kW. This is because the losses of battery charge and discharge are larger than the profit of operating point adjustment in the domain of over 15 kW whose combustion efficiency exceeds certain level. Permitted areas of intermittent operation are determined by the contribution to fuel economy enhancement.

6.3 Voltage Amplification

As shown in Figure 14, "Hybrid Drive" is selected when generating the maximum output in this system. In this case, the motor needs to have enough size to guarantee the system maximum output because the motor directly drives the driveshaft. The efficiency map of the motor is shown in Figure 18. Since the efficient domain of the motor is in the relatively high rotation side, when using low rotation sides, such as a city driving, it is difficult to make the efficient domain agree with an actual operating domain.

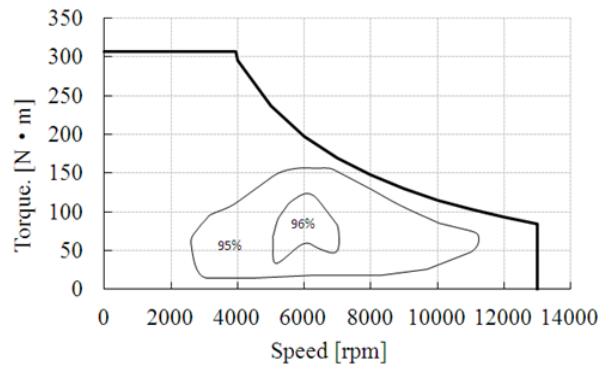


Figure 18: Motor efficiency map with the inclusion of the inverter

Therefore, the output curve of a motor is changed by adjusting motor operating voltage using the VCU according to an actual operating point.

The motor efficiency map in each operating voltage is shown in Figure 19. By reducing motor operating voltage, an efficient domain agrees with an actual operating domain in low load situations. Since high output can be produced from a comparatively small motor by amplifying the battery voltage, voltage amplification contributes not only to efficiency enhancement but to the miniaturization of the motor.

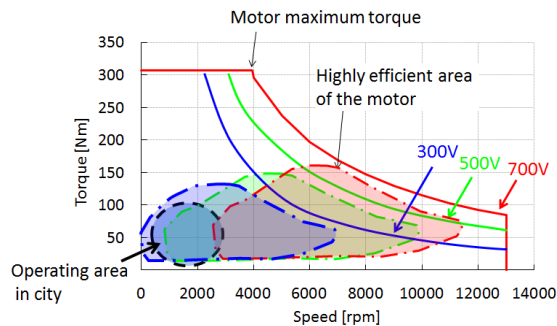


Figure 19: Efficiency enhancement with voltage amplification

6.4 Summary of Efficiency Enhancement Control

The relationship between the control technologies for the efficiency enhancement so far described and the operation modes is shown in Table 3. Power plant efficiency is maximized by enhancing the efficiency in all operation modes

Table 3: Control technologies for efficiency enhancement

	EV drive	Hybrid drive	Engine drive
Adjustment of engine operating points		○	○
Intermittent operation		○	○
Voltage amplification	○	○	

7 Power Management

A schematic drawing of basic power management during "Hybrid Drive" which is the main operation mode of this system is shown in Figure 20. As shown in Figure 16, the battery is charged by generating more power than required in the lower load domain compared with the BSFC lowest point. In contrast, the engine output is suppressed and assisted by the battery output to keep engine operating range efficient in the higher load domain. "EV Drive" is selected in the lower load domain below predetermined level.

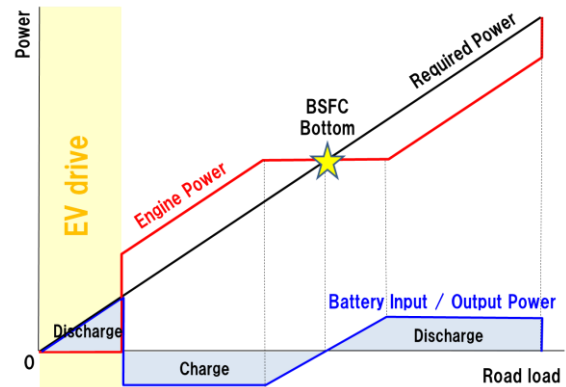


Figure 20: Schematic drawing of basic power management

The amount of charge and discharge to the battery is determined from the overall efficiency point of view according to the balance of the profit of engine operating point adjustment and the losses of charge and discharge.

Actual amount may vary depending on the conditions such as battery SOC (State of charge) and driveability.

The switching point of "EV Drive" and "Hybrid Drive" is changed according to the same reasons.

The energy management control which holds SOC on a proper level is described in the next chapter.

8 Energy Management

In order for the vehicle to operate in the operation modes discussed in the previous chapters, the energy management of the high voltage battery is important. Over-discharging or overcharging of

the high voltage battery are big technical issues in all driving conditions because they not only cause lower fuel economy but decrease the battery durability. In each driving mode, discharging and charging of the high voltage battery is controlled properly from fuel economy, drivability and durability points of view based on the state of charge (SOC). As a result, battery SOC is managed in the appropriate area while maximizing system efficiency.

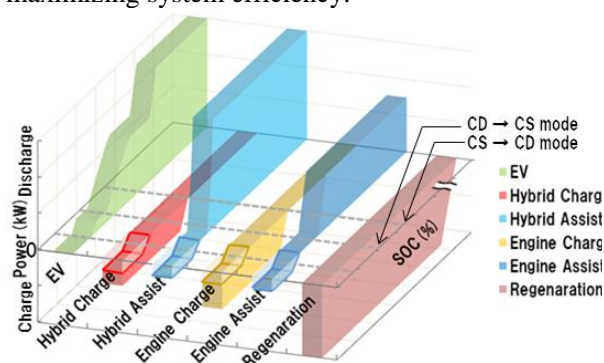


Figure 21: Battery power management

Output and input limitations of the high voltage battery in each operation mode are shown in Figure 21. This power management setting allows choosing "EV Drive" in most cases of a CD mode.

To avoid fuel efficiency deterioration due to wasteful charging, charging in "Hybrid Drive" and "Engine Drive" is permitted in a CS mode only. To recover the stored electricity amount, an electric motor assist is inhibited and the high voltage battery is charged forcibly in the low

SOC situation. Also, the battery is charged as much as possible except full charge condition during regeneration.

In actual energy management, permitted output is determined in real time within the confine of charge and discharge limit as shown in Figure 21. Vehicle speed, engine rpm and SOC transition in an actual driving cycle with the proposed energy management concept are shown in Figure 22. Vehicle speed is indicated in three different colors, "EV Drive (Green)", "Hybrid Drive (Red)" and "Engine Drive (Gray)". "Hybrid Drive" is selected if strong acceleration is required, and "EV Drive" is selected during slight acceleration or deceleration. As mentioned before, intermittent operation between "Engine Drive" and "EV Drive" is performed during slight acceleration or cruise in a high speed situation.

Energy management control is optimized by choosing a proper operating mode in response to the driving condition and adopting engine operating point adjustment during engine activation.

9 Results of Fuel Economy Enhancement

Contributions to fuel economy enhancement of each technical item of the proposed two-motor hybrid system compared to an imaginary conventional gasoline-powered vehicle equipped with a four-stroke gasoline engine without special features such as an Atkinson cycle mechanism and a cooled EGR system are shown in Figure 23.

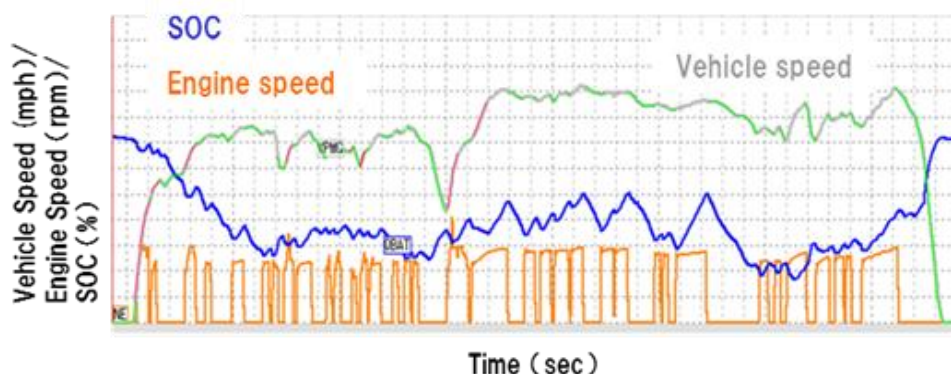


Figure 22: Actual energy management

Fuel economy is enhanced approximately 39% by hybridization utilizing developed two-motor hybrid system and control technologies described in this paper. BSFC of the engine is enhanced approximately 10% by adopting a cooled EGR system and VTEC technology to realize Atkinson cycle operation. The efficiency enhancement of the motor and the generator including the PCU contributes approximately 10% of overall efficiency by the optimization of electromagnetic circuit and the optimization of the motor operating voltage using the VCU. Brake loss reduction as a result of the new electric servo brake system application realizes 8% overall efficiency enhancement compared with a conventional regeneration brake system. Moreover, low rolling resistance tires and aerodynamic drag decrease contribute approximately 3% of overall efficiency enhancement. As a result, fuel economy is enhanced approximately 70% compared with a conventional vehicle.

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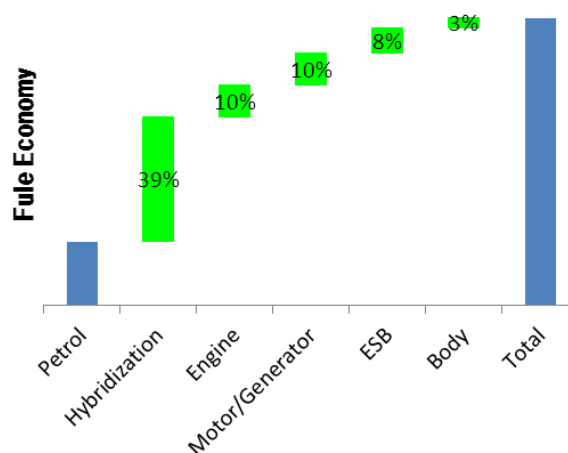


Figure 23: Contributions to fuel economy enhancement

10 Summary

The following fuel consumption values are achieved while maintaining sufficient driving performance and marketability as a mid-class sedan by installing a newly developed two-motor plug-in hybrid system into 2014 Accord plug-In.

1. EV range: 13 mile
2. Fuel economy:
 - Charge depleting: 115 MPGe
 - Charge sustaining: 46 MPG