

Development of High-efficiency CVT for 2020 Model Year CITY

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ABSTRACT

A CVT has been developed for use in the 2020 model year CITY with the aim of realizing a good balance between fuel efficiency and power performance.

As new mechanisms, the developed CVT employs a belt with a modified rocking position, pulleys with multiple V-surface shapes, and mechanical and electric oil pump systems in series connection. The application of these technologies has made it possible to reduce the main sources of loss in a metal pushing V-belt CVT and to increase power transmission efficiency. When these new mechanisms were combined, CVT control was optimized in order to help ensure a reduction of loss in the CVT itself.

In addition, the driver's intention in accelerating the vehicle is realized by switching CVT control in order to help ensure that there is no decline in power performance, due to the application of control that optimizes fuel efficiency. By setting drive power as the target parameter for CVT shift control, it has been possible to help avoid decline in drive power. Furthermore, the application of stepped shift has meant that vehicle speed follows engine speed linearly, and vehicle occupants experience an increase in drive power.

As a result, the CVT has realized a reduction of 5.7 g/km in CO₂ emissions against the previous unit in the New European Driving Cycle mode. In addition, the 2020 model year CITY meets the 100 g/km or below CO₂ emissions standard for the second phase of Thailand's eco-car project.

1. Introduction

Today, countries throughout the world are increasing the stringency of their environmental regulations as a response to global environmental issues. This global trend is accelerating the transition toward electrification of automotive powertrains. However, in nations in which increasing the utilization of electric vehicles is not an easy matter, for example emerging nations, realizing increased fuel efficiency in conventional vehicles that use internal combustion engines as their sole source of drive power is an urgent matter. Against this background, the application of continuously variable transmissions (CVT) is increasing, given that they are a transmission type able to operate internal combustion engines in the zone of high thermal efficiency. In addition to Honda, automakers in Japan and overseas are applying CVT in a wide range of vehicle types, from light vehicles to small and medium-sized vehicles. Figure 1 shows a breakdown of loss in a metal pushing V-belt CVT in JC08 mode⁽¹⁾. As this figure indicates, loss

resulting from the metal pushing V-belt and the oil pump accounts for more than 60% of total loss. Given this, a variety of measures are being applied to the mechanical parts that are responsible for major loss. Measures including

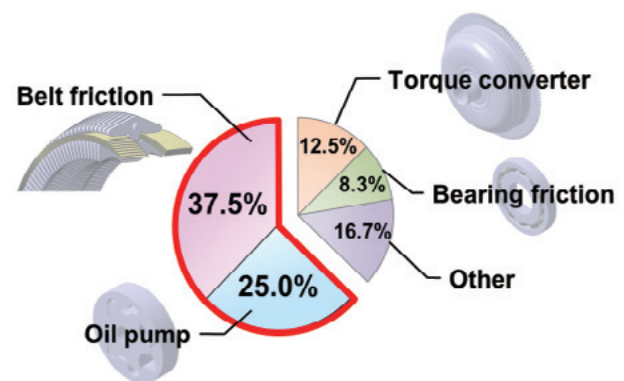


Fig. 1 Breakdown of power consumed in CVT

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the use of CVT provided with starting gears⁽²⁾ are being employed as a response to belt loss. Measures employed to respond to oil pump loss include the application of coaxial two-port oil pump systems⁽³⁾. As this indicates, while CVTs offer good automotive fuel efficiency performance, there remains considerable margin for increasing their power transmission efficiency as transmission systems.

The development discussed in this paper set out to reduce the major losses in metal pushing V-belt CVTs in order to comply with various national environmental regulations, in particular the regulations associated with the second phase of Thailand's eco-car project (Eco2). In addition, the goal for the new CITY was to balance a level of fuel efficiency producing CO₂ emissions of 100 g/km or less in the New European Driving Cycle (NEDC) mode with good power performance.

2. Development Aims

In a metal pushing V-belt CVT (Fig. 2), the belt is sandwiched between a fixed pulley and a movable pulley, and friction force transmits power from the primary (drive) pulley to the secondary (driven) pulley. Because the position of the movable pulley can be changed steplessly on the drive side and the driven side using hydraulic thrust,

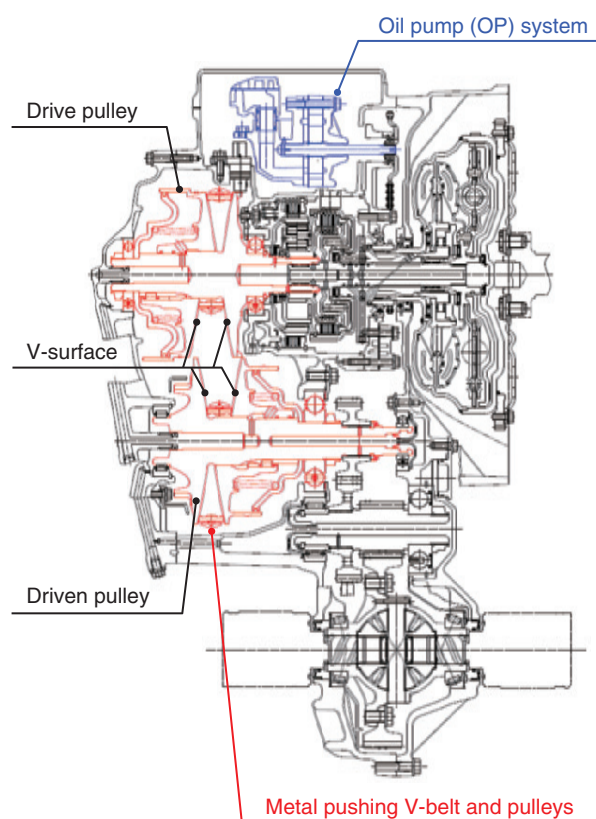


Fig. 2 Main sections of new CVT

the position of the belt wound around the pulleys can also be changed steplessly, making it possible to realize stepless shift. The ability to steplessly select the pulley ratio makes it possible to maintain the zone of high thermal efficiency in an internal combustion engine. As a result, the application of this transmission type is expanding as it increases automotive fuel efficiency.

Due to the component configuration of metal pushing V-belts, there are numerous slipping sections, and as a result, loss occurs in the interior of the belt, which is dependent on the winding diameter of the pulleys⁽⁴⁾. A single oil pump responds to the differing hydraulic oil conditions demanded by components, including the pulleys, the torque converter, and the clutch, in addition to demands for lubrication. Because of this, there is a constant demand for high-pressure and high-flow-rate work from the oil pump, and oil pump loss increases as a result⁽⁵⁾. The belt and the pulleys transmit power via friction, and this necessitates a high clamping pressure on the pulleys. This high level of force affects loss in the metal pushing V-belt, which has a large number of slipping sections, as a slipping load. In addition, oil pump work increases in proportion to the level of clamping pressure on the pulleys, and this increases loss. In order to increase fuel efficiency, the engine employed in the new CITY has been changed from the previous 1.5 L naturally aspirated unit to a 1.0 L turbocharger-equipped unit. To respond to the change in the output characteristic due to this change in the internal combustion engine, cooperative powertrain control (G-design shift) that sets drive power as a target value has been applied.

Based on the above, the following three points were set as the orientation for reduction of loss.

- (1) Reduction in friction loss originating in slipping in the interior of the metal pushing V-belt.
- (2) Optimization of the oil pump work necessary for the CVT by means of dividing work between hydraulic pressure and oil flow rate.
- (3) Optimization of CVT control in order to realize reduction of loss without a reduction in power performance.

3. Applied Technologies

A new belt and pulley assembly and a new oil pump system (Fig. 2) were applied in order to reduce the main losses in the metal pushing V-belt CVT.

3.1. Belt and Pulley Assembly

A metal pushing V-belt is made up of elements and rings. When the belt is wound between the pulleys, a geometric difference between the radius of rotation of the elements and the ring within the pulleys is generated. Because the elements and the ring do not mutually constrain each other, this difference in the radius of rotation generates a difference in rotational speed within the interior of the metal pushing V-belt. Due to slipping as a result of

this difference in rotational speed, the elements and ring generate friction loss in the interior of the belt. Friction loss per unit of time is given by the product of the coefficient of friction of the slipping sections, the vertical load generated on the slipping sections, and the relative speed. Based on this loss relationship, friction loss was reduced by reducing the slipping distance and load of the slipping sections. Table 1 shows the main specifications of the belt and pulleys employed in the new CVT. The reduction of these friction losses made it possible to increase power transmission efficiency by 0.9% in relation to the average pulley ratio range⁽⁴⁾.

3.1.1. Change in rocking position

Metal pushing V-belts transmit power by means of the action of the elements pushing against each other. By reducing the size of the elements at the position at which they push against each other (rocking position) and the difference in the radius of rotation between the elements and the rings within the pulleys, it was possible to reduce the slipping distance by means of the mutual difference in rotational speed. The slipping distance of the slipping sections of the belt is proportional to the difference in radius.

As shown in Table 1 and Fig. 3, the reduction of the size of the elements at the rocking position from 1.00 mm to 0.55 mm made it possible to geometrically reduce the amount of slipping by 45%.

3.1.2. Multiple V-surface pulleys

CVTs determine the pulley ratio in response to the transmitted torque while varying the clamping pressure on the pulleys in accordance with the operating status of the vehicle. The relationship between the clamping pressure on the drive and the driven pulleys also changes each time this happens. By narrowing the angle of the smaller-diameter side of the pulley V-surfaces at this time, it is possible to reduce the pulley clamping pressure necessary for the transmission of torque. This makes it possible to reduce the load on the slipping sections of the metal pushing V-belt.

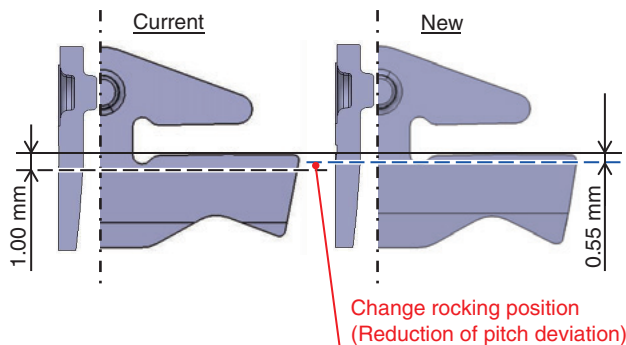


Fig. 3 Comparison of current and new elements

Table 1 Specifications of pulley and belt

Item		Current model	New model
Pulley	Distance between pulley axes	156 mm	156 mm
	V-surface	Single angle 11 deg	Multiple angle 9 deg / Round
Belt	Element width	24 mm	24 mm
	Rocking position	1.00 mm	0.55 mm
	V-surface	Single angle	Multiple angle
		11 deg	9 deg / Grooved
			Curved / No groove
	#1 ring diameter	208.8 mm	208.8 mm

Conversely, by increasing the angle of the larger-diameter side of the pulleys, it is possible to reduce the pulley clamping pressure that determines the pulley ratio. As a result, the maximum system hydraulic pressure necessary for the CVT (P_H) can be reduced. In the development under discussion, these characteristics were made use of in order to realize a multiple V-surface shape for the pulleys. The V-surface shapes of the elements were formed into a composite shape the same as the shape employed in the pulleys to help ensure the stability of power transmission when the pulleys are changed (Fig. 4). Because reducing P_H also makes it possible to reduce oil pump work, this contributes to the reduction of oil pump loss.

3.2. Mechanical and Electric Oil Pump Systems in Series Connection

Oil pump work is determined by the product of the hydraulic pressure and the oil flow rate demanded to generate the necessary drive force. Unlike other automatic transmissions, two types of work are necessary for a CVT. In addition to the low-pressure, high-flow-rate necessary for the torque converter and lubrication, high-pressure, low-flow-rate is also necessary for belt-clamping pressure and the connection of the clutch. Because of this, it is necessary

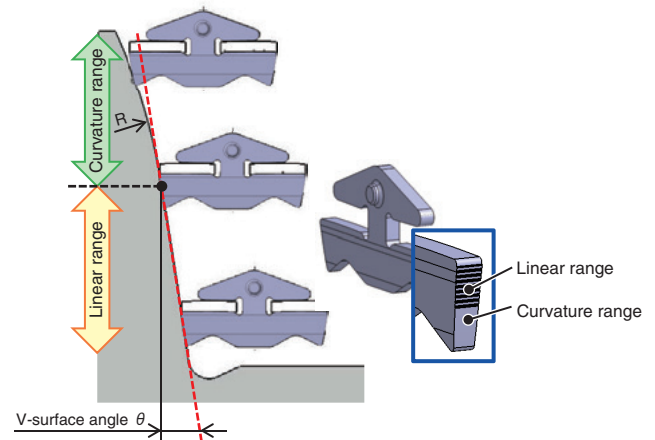


Fig. 4 Pattern diagram of pulley and belt

to realize the high pressure necessary for belt-clamping pressure and the high flow rate that makes it possible to maintain the state of lubrication using a single oil pump. Work is therefore demanded from the oil pump within the greatest scope that realizes both of these demands, and as a result oil pump work in the high-pressure, high-flow-rate zone becomes oil pump loss (Fig. 5).

However, the work of mechanical oil pumps (mechanical OP) depends on engine speed. In order to optimize oil pump work, it is necessary to employ a drive system that is independent of engine speed, making it possible to realize efficient rotation under a variety of operating conditions. An electric oil pump (electric OP) was therefore employed in addition to the mechanical OP⁽⁵⁾. The use of two different oil pumps has made it possible to divide the two types of work and reduce oil pump loss. In configuring the oil pump system, it was decided to employ a hydraulic circuit that would not hinder operation even if the electric OP malfunctioned (Fig. 6). The use of two oil pumps in a series configuration helps to ensure that the reference hydraulic pressure is constantly provided by the mechanical OP. The electric OP provides

high pressure and a low flow rate by increasing the pressure of the oil sent from the mechanical OP.

As a result, there is no necessity for the oil pump system to produce high pressure and a high flow rate, thus making it possible to reduce loss. In addition, because the drive system is motor driven and therefore does not depend on engine speed, the amount of oil pump work can be freely determined, making it possible to optimize oil pump work (Fig. 7).

The size of the motor that drives the electric OP was determined with consideration of the work of the alternating current generator (ACG) necessary for the reduction of oil pump loss. In the developed CVT, fuel efficiency was prioritized, and a 100 W motor was selected based on the amount of work necessary for the transmission employed in the CITY (Fig. 8). The main specifications of the oil pump system that was applied are shown in Table 2. The application of these technologies increased power transmission efficiency by 0.7% in relation to the average pulley ratio range.

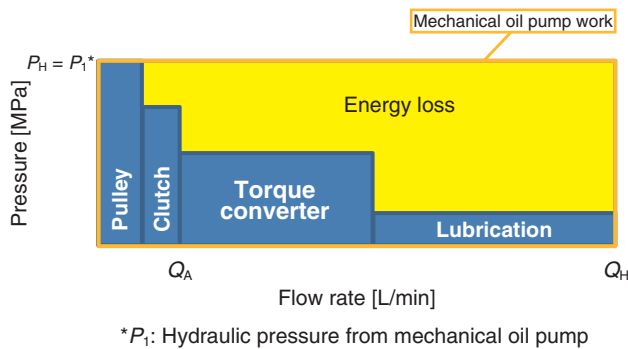


Fig. 5 Oil pump work in CVT

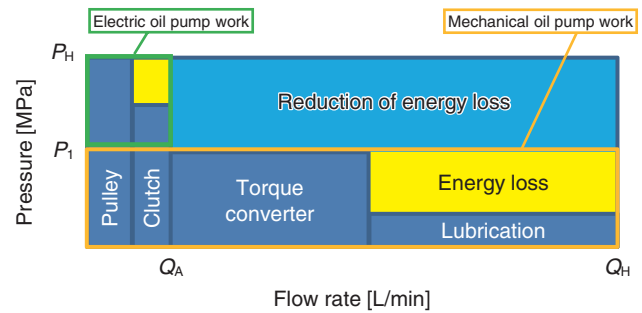


Fig. 7 New oil pump system for CVT

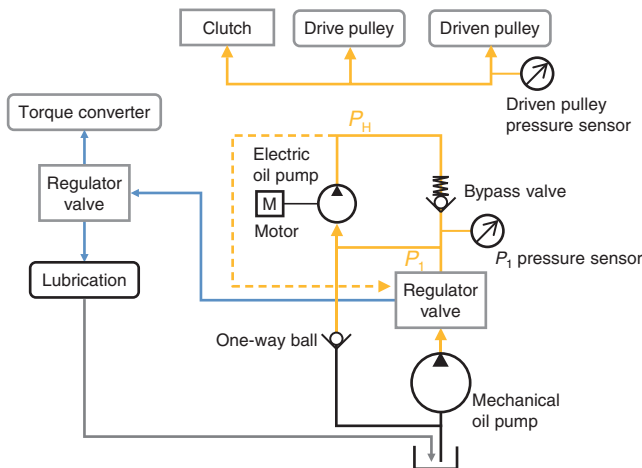


Fig. 6 Hydraulic circuit

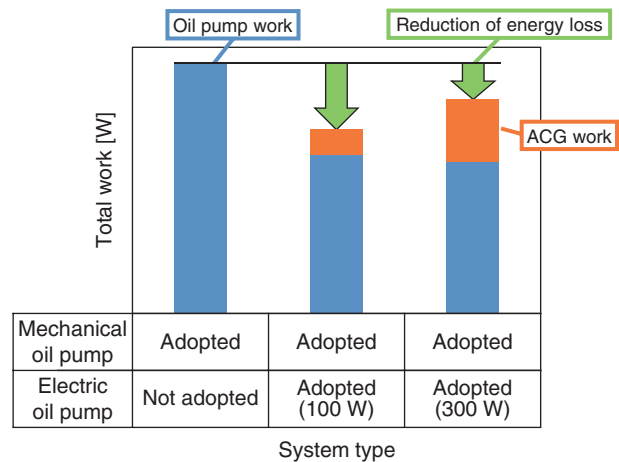


Fig. 8 Effect of reduction of energy loss

Table 2 Specifications of new oil pump system

Item		Current model	New model
Drive system	Mechanical	Adopted	Adopted
	Flow rate	Up to 72 L/min	Up to 72 L/min
	Discharge pressure	0.2 - 4.9 MPa	0.2 - 4.9 MPa
	Electrical	Not adopted	Adopted (100 W)
	Flow rate	—	Up to 5.8 L/min
	Discharge pressure	—	0.2 - 1.8 MPa

4. CVT Control

The developed CVT employs new technologies in two mechanisms: the belt and pulley system and the oil pump system. In addition to these technologies, other constituent components were redesigned in order to reduce loss. In relation to each of the loss reduction results achieved in this development, CVT control was optimized in order to realize power transmission efficiency in the unit as a CVT. In addition, the application of G-design shift in order to balance fuel efficiency with power performance made it possible to realize a linear acceleration feel.

4.1. Fuel Efficiency

The pulleys employed in the CVT are at once rotating bodies and hydraulic mechanisms. The drive and driven pulley shafts are connected by the metal pushing V-belt, and a mutual pulling force acts between the two shafts. As a result, a high load is applied to the bearings. In addition, the movable pulley is provided with a hydraulic chamber, and the metal pushing V-belt is sandwiched between the pulleys by hydraulic pressure supplied by the oil pump. In other words, at the same time as the oil pump work changes due to the necessary pulley clamping pressure, the load on the bearings and other components also changes. In the newly applied belt and pulley system and oil pump system, an electric OP was employed with the aim of boosting the pulley clamping pressure. Because electric OP drive consumes power, drive control that maintains efficiency in relation to the status of vehicle operation has been applied. The use of a multiple V-surface shape in the belt and pulley system has reduced the necessary pulley clamping pressure (i.e., the maximum hydraulic pressure, P_H). The reduction of the belt clamping pressure has had the effect of reducing friction loss between the belt and the pulleys. The adoption of mechanical and electric oil pump systems in series connection have made it possible to support high-pressure, low-flow-rate work via the electric OP. In other words, the higher the maximum hydraulic pressure, P_H ,

in the system, the greater the effect in loss reduction.

Based on consideration of the differences between the loss reduction methods employed in each of these mechanisms, the aim was to drive the system more efficiently as a CVT. The fact that the operation of the electric OP could be stopped in accordance with vehicle operating conditions made it possible to control power consumption. Utilization of the advantages provided by these choices of mechanism was reflected in CVT control.

Figure 9 shows the operation of the oil pump system during actual vehicle operation, in addition to power transmission efficiency and the effect of each mechanism in reducing loss.

(1) Idle stop (When the vehicle is stopped)

When the vehicle is idling, there is no change in fuel efficiency even if some engine power is used for the mechanical OP drive. The electric OP therefore does not operate as was previously the case. In addition, an idle stop system has been employed in the new CITY based on considerations of fuel efficiency. When the idle stop system is in operation, the electric OP is driven in order to compensate for the delay in the recovery of pulley clamping pressure when the engine is restarted. Driving the electric OP results in work for the ACG, but makes it possible to control fuel consumption when the vehicle is idling.

(2) Vehicle take-off

When the vehicle takes off, the torque converter amplifies torque, and the necessary pulley clamping pressure increases. In addition, when shifting from a low pulley ratio, the oil flow rate associated with shift is demanded. The electric OP realizes the flow rate for shift while also increasing pulley-clamping pressure, P_H , making it possible for the mechanical OP to reduce the hydraulic pressure generated to the level of lubrication pressure. As a result, it is possible to apportion oil pump work and realize a considerable reduction in drive loss in the oil pump system.

(3) Acceleration from take-off

For acceleration from take-off, drive force is reduced while the vehicle speed is increased. At this time, the pulley ratio is gradually shifted to the high side. In other words, both the transmitted power and the speed of shift are lower than when the vehicle takes off. In addition, the use of multiple V-surface pulleys made it possible to reduce the necessary clamping pressure, P_H , for the pulleys. It is therefore possible to maintain the work of the mechanical OP at lubrication pressure by increasing the drive speed of the electric OP. As a result, the increased work of the oil pump system only represents an increase in electric OP drive speed, and it is possible to maintain an effect of reduction in loss equivalent to that at vehicle take-off.

(4) Cruise

When the vehicle is cruising, the pulley ratio

is constantly maintained on the high side. High pulley ratios represent a zone in which the power transmission efficiency of the multiple V-surface pulleys and the belt with its change in rocking position are high, and this contributes greatly to increased fuel efficiency. In addition, because it is possible to reduce the necessary pulley-clamping pressure, P_H , and it is not necessary to change the oil flow rate for shift, it is also possible to control the electric OP drive speed. As a result, it is possible to realize loss reduction in both the belt and pulley system and the oil pump system. In addition, there has been a major effect in comprehensively reducing friction loss in a variety of components, such as the bearings. At this time, if it is judged that there is no loss reduction effect with consideration of electric OP drive power in relation to the total work of the oil pump system, the electric OP is not activated.

(5) Re-acceleration from cruise

When the vehicle re-accelerates after cruising, a low pulley ratio is employed in order to help ensure drive force. The necessary pulley-clamping pressure, P_H , increases as a result of the shift to a low pulley ratio. Because the amount of shift is small at this time, the necessary oil flow rate is also small. By using the electric OP to respond to the increased work of the oil pump system, it has been possible to reduce the work of

the mechanical OP, thus reducing drive loss in the oil pump system.

(6) Deceleration

When the vehicle brakes, fuel injection in the engine is stopped. Because no fuel is being consumed, the operation of the electric OP also stops. Although no fuel is being consumed, the effect of increased power transmission efficiency in the belt and pulley system and other components makes it possible to considerably reduce drag loss in the transmission.

As this indicates, it has been possible to implement CVT control that makes it possible to adequately utilize the loss reduction effect in increasing fuel efficiency.

4.2. Drive Power Design

In addition to the application of the new transmission, numerous modifications have been made to the new CITY in order to increase fuel efficiency. The engine employed in the vehicle has been changed from a naturally aspirated 1.5 L unit to a 1.0 L turbocharger-equipped unit in order to realize an internal combustion engine with increased fuel efficiency. The reduction in displacement has allowed fuel consumption to be controlled, while the use of a turbocharger has made it possible to maintain the previous level of maximum power. However, at times such as vehicle take-off, the engine maintains the characteristics of a naturally

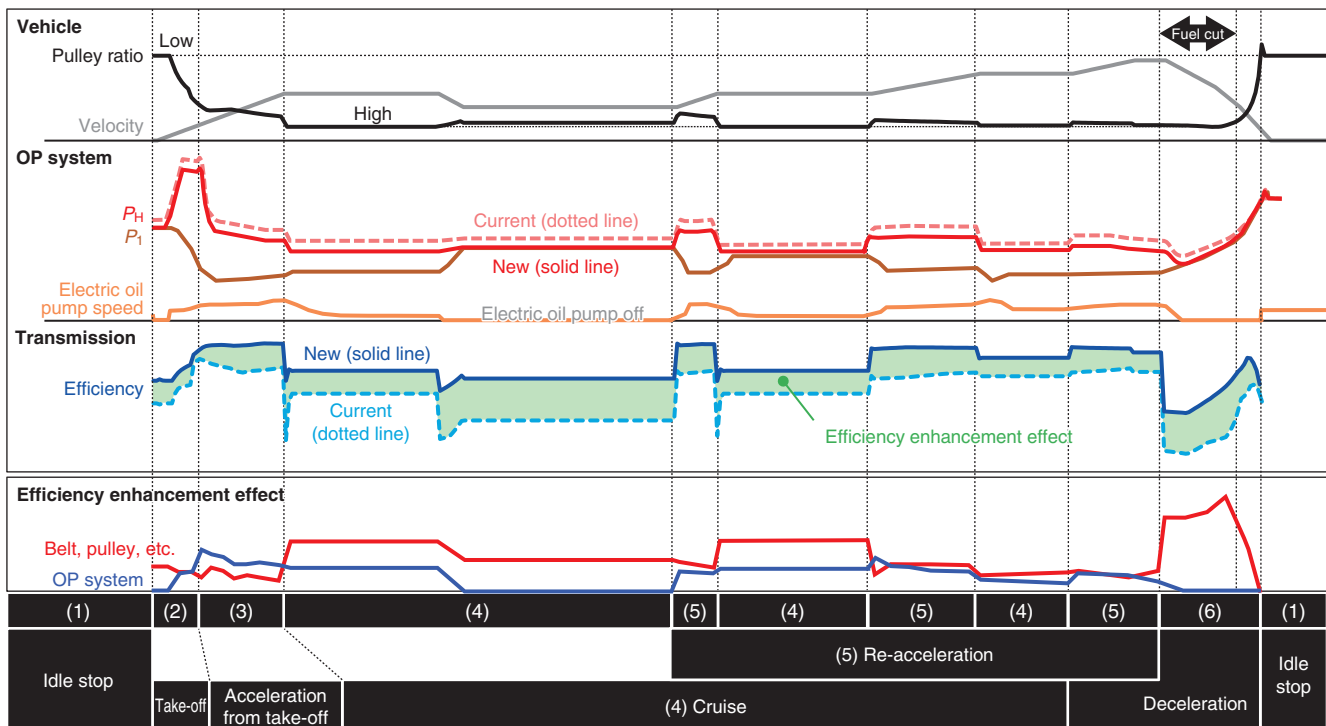


Fig. 9 Operation of new CVT

aspirated 1.0 L unit until the turbocharger commences operation. In other words, it takes a considerable amount of time until maximum output is realized. In response to this, the CVT balances fuel efficiency and power performance by switching shift control based on the driver's intention to accelerate. Determining the pulley ratio in response to the target drive force in order to maintain the drive feel has made it possible to realize control with no drop in drive force. As a result, it has been possible to realize a linear acceleration feel, with vehicle occupants experiencing no differences in the engine power characteristic. In addition, when the accelerator is fully depressed, fully open step-shift control that shifts like a stepped transmission is employed. As a result, vehicle speed linearly follows engine speed, and vehicle occupants experience an increase in drive power. Figure 10 shows a comparison of data measured during take-off and acceleration with the previous model. After the maximum drive power is generated, the target value is followed to help ensure that drive power does not fall, giving the new CITY a good drive feel.

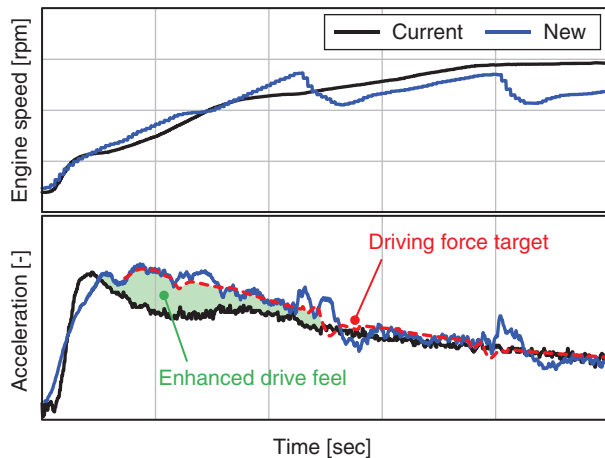


Fig. 10 Step-shift operation

5. Fuel Efficiency and Power Performance

The 2020 model year CITY in which the developed CVT is employed realizes CO₂ emissions of 100 g/km or less in NEDC mode. The reduction of loss in the CVT reduced CO₂ emissions by 5.7 g/km. In addition, as shown in Fig. 11, considerable increases in fuel consumption performance and power performance have been realized compared with the previous model.

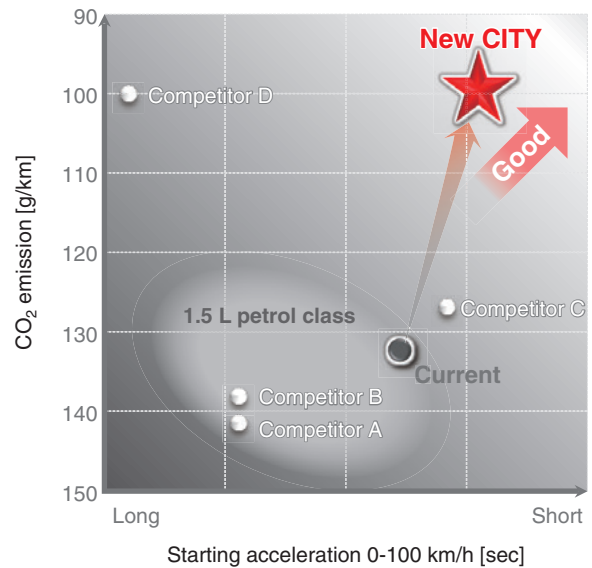


Fig. 11 Performance of new CITY

6. Conclusion

A high-efficiency CVT has been developed as the transmission for the 2020 model year CITY. The application of the developed CVT, which employs new technologies and a new control system, has balanced fuel efficiency and power performance. The CVT has reduced CO₂ emissions by 5.7 g/km compared with the previous model. In addition, the new CVT meets the Eco2 CO₂ emissions standard of 100 g/km or below.

- (1) As new technologies, a belt with changed rocking positions and pulleys employing multiple V-surface shapes were employed. In addition, mechanical and electric oil pump systems in series connection were employed. As a result, power transmission efficiency has been increased by 0.9% in the belt and pulley system and 0.7% in the oil pump system in relation to the average pulley ratio range.
- (2) In adopting the two new technologies described above, CVT control was optimized in order to make it possible to fully take advantage of the loss reduction effect.
- (3) Shift control that employs drive power as a target was applied in order to maintain the vehicle's drive feel while optimizing CVT control for fuel efficiency. In addition, the adoption of stepped shift has meant that vehicle speed follows engine speed linearly, and vehicle occupants experience an increase in drive power.

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