Control techniques supporting fuel economy and driveability of a new 9-speed automatic transmission for rear-wheel-drive vehicles

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Summary

The new 9-speed automatic transmission for rear-wheel-drive vehicles that went into production in September 2019 incorporates numerous control techniques for eliciting the full benefits of additional speeds. Among them, this article describes control techniques adopted for the first time that contribute to improving fuel economy and driveability. Two driving situations are presented as examples to illustrate the shift control details and the issues that have been resolved.

1. Introduction

More speeds have been added to stepped automatic transmissions in recent years from the perspective of satisfying concerns about the environment and fuel economy while simultaneously providing the desired power performance. However, although adding more speeds can be expected to improve environmental friendliness, fuel economy and power performance, there is also concern that increasing the number of shifts will worsen shift busyness and response, among other adverse effects.

The new 9-speed automatic transmission (9AT) for rear-wheel-drive vehicles has been developed to resolve these issues, and it also incorporates numerous control techniques for eliciting the full benefits of additional speeds.

This article describes two driving situations as typical examples where the shift control techniques incorporated in the new 9AT for the first time contribute to improving fuel economy and driveability.

2. Configuration of new 9AT gear train

This section explains the configuration of the new 9AT gear train. Figure 1 is a skeleton of the new 9AT, and the chart in Fig. 2 shows the operation of the shift elements. The shift patterns of each gear are configured such that not only are one-gear upshifts and downshifts from the current gear possible, but also skip-shifting such as 1st gear⇔3rd gear, 3rd gear⇔5th gear, 5th gear⇔7th gear, 7th gear⇔9th gear can be executed. Shifts are possible by just releasing one element and engaging one element (referred to here as single transition shifts).

The arrows in Fig. 3 connect the shift patterns that can be executed by single transition shifts; the different colored lines indicate gears that are skipped. In addition to shifting between adjacent gears, it is seen that 11 shift patterns are possible by single transition shifts. The control techniques developed to solve the issues mentioned earlier by using these characteristics are explained in section 3.

3. Control techniques for obtaining both fuel economy and driveability

Specific examples are presented to show how the shift control techniques contribute to improving fuel economy and driveability in the following two driving situations. The issues and control measures for addressing them are explained.

1. Downshift when decelerating during fuel cut-off
2. Power-on downshift by depressing the accelerator pedal

3.1 Downshift when decelerating during fuel cut-off

3.1.1 Issue of lengthening fuel cut-off duration when decelerating

For the purpose of improving fuel economy, a longer

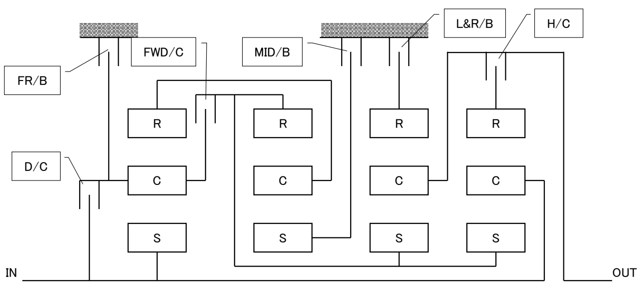

Fig. 1 Skeleton diagram of the new 9AT

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Gear	MID/B	L&R/B	FR/B	D/C	H/C	FWD/C
1	●	●				●
2		●		●		●
3	●	●		●		
4	●	●			●	
5	●			●	●	
6				●	●	●
7	●				●	●
8			●		●	●
9	●		●		●	

Fig. 2 Shift elements of the new 9AT

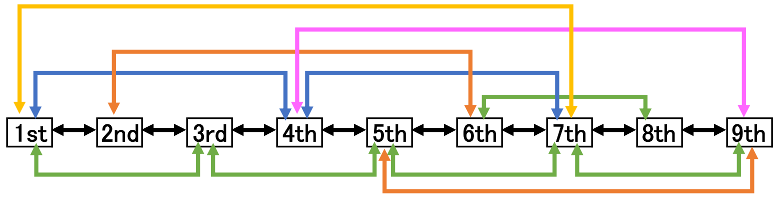

Fig. 3 Single transition shift patterns

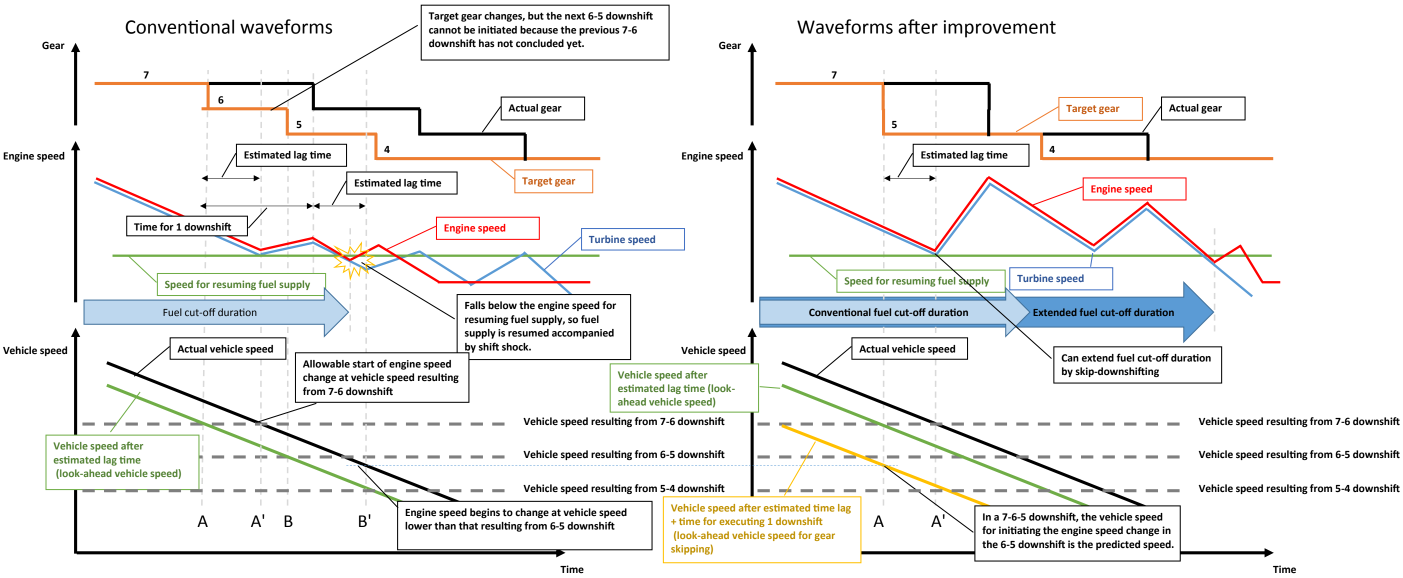

Fig. 4 Downshift during vehicle deceleration

fuel cut-off duration than before is required today during power-off deceleration. In order to continue fuel cut-off to the low gear range, it is necessary to downshift before the engine speed reaches the level for resuming fuel supply.

Adding more speeds, however, increases the number of shifts executed during deceleration. Consequently, in the conventional waveforms shown in Fig. 4, shifting cannot be initiated at the desired timing B depending on the vehicle deceleration rate and shift time. There was concern that fuel supply would be resumed, thus precluding any fuel economy improvement. There was also concern that shift shock might be worsened by an abrupt change in engine torque due to unintentional resumption of fuel supply during shifting.

Therefore, a new shift control technique was adopted to obtain both continuation of fuel cut-off and resumption of fuel supply at the desired timing, as explained below.

3.1.2 Attainment of longer fuel cut-off duration during deceleration

The downshift timing during deceleration has previously been commanded taking into account the lag time between the issuance of the shift command and the onset of the change in engine speed induced by downshifting. The control adopted this time for the 9AT also estimates whether the change in engine speed due to the next downshift can be achieved at the desired timing. If it is judged that it cannot be achieved at the desired timing, the transmission is commanded to skip-downshift aggressively such as by executing 9-7 and 7-5 shifts.

Skip-downshifting enables fuel cut-off to be continued without the engine speed unintentionally dropping to the level for resuming fuel supply. It also prevents worsening of shift shock caused by interference between shifting and fuel supply resumption.

The specific control method is explained here. As indicated by the conventional waveforms in Fig. 4, the conventional control technique calculates the estimated lag time from a 7-6 shift command to the onset of the change in engine speed and also the vehicle speed (referred to here as the look-ahead vehicle speed) after the estimated lag time based on the current rate of vehicle deceleration. The start of the 7-6 downshift is commanded at timing A where the look-ahead vehicle speed drops below the speed that results from the 7-6 downshift. If the 7-6 downshift can be initiated at timing A as commanded, the engine speed

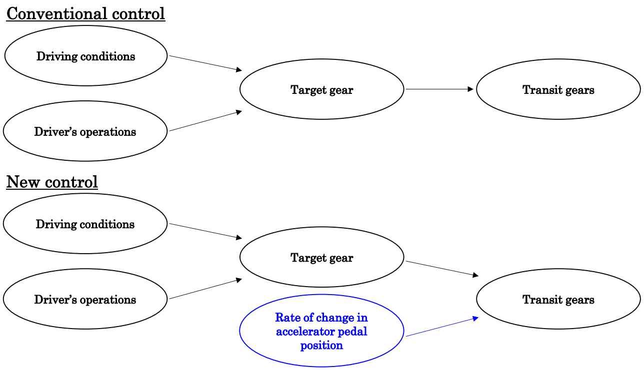

Fig. 5 Determination of transit gears

begins to change at timing A' where the actual vehicle speed is the speed produced by the 7-6 downshift. However, in the case of sudden deceleration or for some other reason, the subsequent 6-5 downshift cannot be initiated at the targeted timing B because the previous 7-6 downshift has not concluded yet. Accordingly, the vehicle speed when the engine speed begins to change is lower than the speed resulting from the 6-5 downshift.

As indicated by the improved waveforms in Fig. 4, in addition to calculating the look-ahead vehicle speed following the estimated lag time, the new control technique also estimates the vehicle speed (referred to here as the look-ahead vehicle speed for gear skipping) after the estimated lag time plus the time for executing one downshift, as noted in the conventional waveform in the figure. At timing A commanded by the conventional control technique for initiating the 7-6 downshift, if the look-ahead vehicle speed for gear skipping is below the speed resulting from the 6-5 downshift, in the event 7-6 and 6-5 downshifts are executed, it means that at the time of the 6-5 downshift the change in engine speed begins when the vehicle speed is below that resulting from the 6-5 downshift. Therefore, in this case the 7-5 downshift command makes it possible to decelerate as far as 5th gear without any resumption of fuel supply. In addition, because a 5-4 downshift can also be executed at the desired timing, fuel cut-off can be continued even during the 5-4 downshift.

As a result, assuming that fuel supply is resumed in 4th gear, the fuel cut-off duration can be continued and extended as indicated by the improved waveforms in Fig. 4.

3.2 Power-on downshift by depressing the accelerator pedal

3.2.1 Effect of adding more speeds on improving driveability and issues involved

Adding more speeds has the effect of making it possible to provide the fine-tuned driving force demanded by drivers. However, the transmission must pass through more gears than before to reach the driving force that drivers want. This poses the issue that a lag may occur before the driving force demanded by drivers is reached. The shift control of the 9AT was improved to provide the fine-tuned driving force that drivers demand and without any lag either.

3.2.2 Determination of transit gears

The 9AT incorporates a control technique that optimizes the number of transit gears in order to transition to the desired fine-tuned driving force without any lag. As shown in Fig. 5, the conventional control technique determines the optimum target gear based on the driving conditions and the driver's operations; it selects the minimum number of transit gears to be followed for reaching the target gear.

The new control technique refers to the rate of change in the accelerator pedal position when selecting the number of transit gears. Accordingly, when there is a large rate of change in the accelerator pedal position, the number of transit gears to reach the target gear is minimized, thereby enabling a quick transition to the driving force demanded by the driver. When there is a small rate of change in the accelerator pedal position, the number of transit gears to reach the target gear is increased, thus delivering fine-tuned driving force that traces the driving force desired by the driver.

Moreover, this control technique is capable of real-time judgments so as to provide driving force that follows the driver's various accelerator pedal inputs. For example, in shifting from 9th gear to 4th gear, the single transition shift patterns in Fig. 3 show that the following transit gears can be selected: 9-4, 9-5-4, 9-7-4, 9-7-5-4, 9-7-6-5-4, 9-8-7-4, 9-8-6-5-4, 9-8-7-5-4, and 9-8-7-6-5-4. The following are examples related to the accelerator pedal position. As shown in Fig. 6, a 9-4 shift is selected when the driver depresses the accelerator pedal fast and a 9-8-7-6-5-4 shift is selected when the accelerator pedal is depressed gently. When the depression of the accelerator pedal produces a curved pattern, the number of transit gears is reduced in the first half and increased in the second half for a 9-7-5-4 shift sequence. When it produces an arch-shaped pattern, the number of transit gears is increased in the first half and reduced in the second half for a 9-8-7-4 shift sequence.

Because the transit gears are selected in real time in this way to match the accelerator pedal position, the 9AT can provide the fine-tuned driving force demanded by the driver and without any lag.

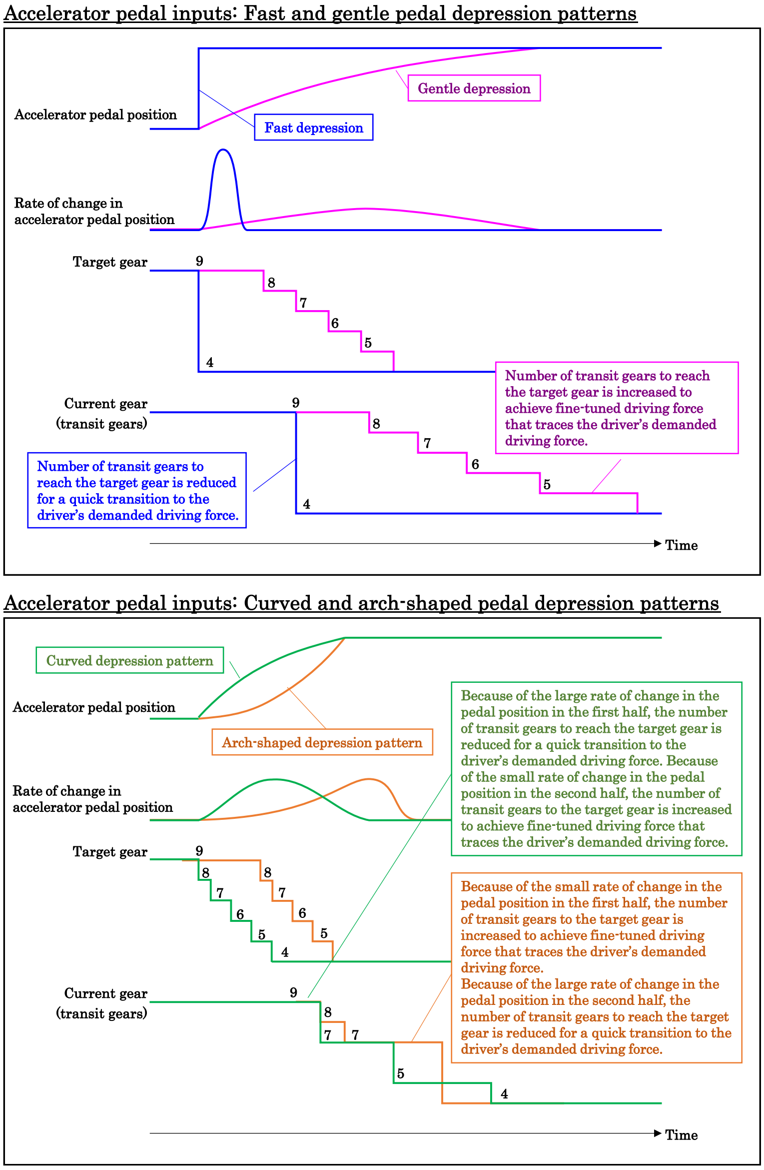

Fig. 6 Accelerator pedal inputs and transit gears

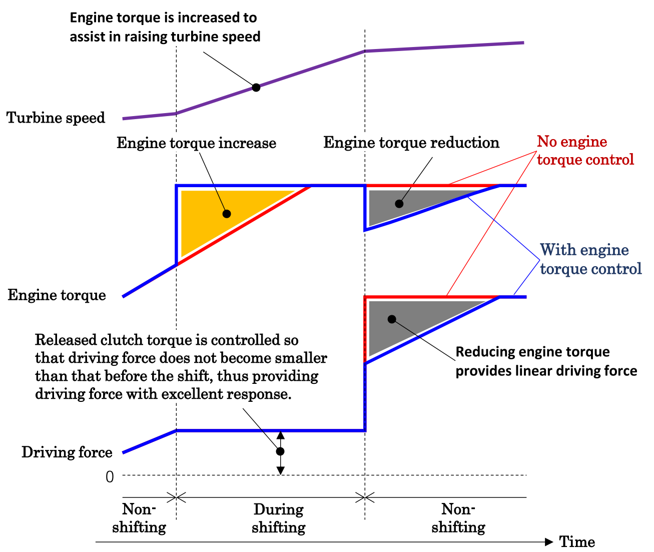

Fig. 7 Provision of smooth driving force with excellent response

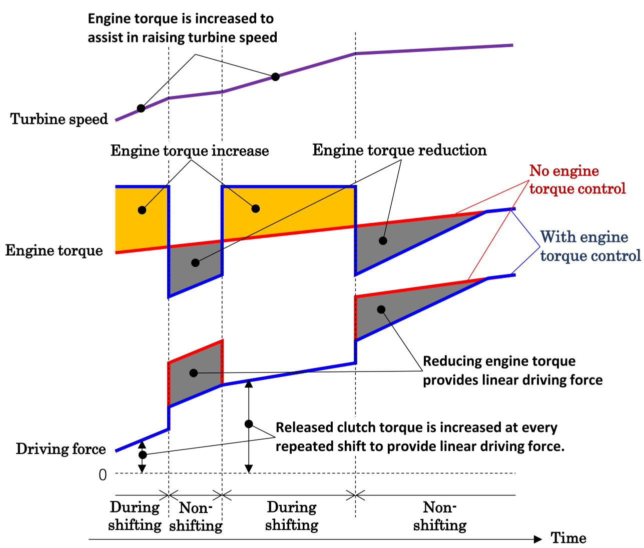

Fig. 8 Provision of smooth, fine-tuned driving force

3.2.3 Determination of clutches and engine torque

As explained in the preceding subsection, there are situations where priority is put on reaching the target driving force and situations where preference is given to providing fine-tuned driving force. The allocation of clutches and engine torque in each case must be optimized in order to obtain driving force matching the objective of the situation.

As shown in Fig. 7, in situations where priority is put on reaching the target driving force, engine torque is increased during shifting to assist in raising the turbine speed. The released clutch torque is also reduced so as not to obstruct the increase in turbine speed, which shortens the shift time. However, if the released clutch torque is reduced too much, driving force will decrease excessively during shifting, giving the driver a feeling of insufficient acceleration. To avoid that, the released clutch torque is controlled so that driving force does not become smaller than it was before the shift. Moreover, to ensure a smooth driving force transition after the completion of the shift, engine torque is reduced for resuming driving force smoothly. This provides smooth driving force with excellent response.

Figure 8 shows an example where preference is given to providing fine-tuned driving force. In this case, the released clutch torque in each shift is controlled so that driving force is increased in a step-like manner every time a shift is repeated. In addition, engine torque is increased during shifting to assist in raising the turbine speed and thereby shorten the shift time. Following the completion of the shift, engine torque is reduced and the driving force between shifts is reduced, thereby decreasing the difference in driving force between the intervals of shifting and non-shifting. This results in smooth, fine-tuned driving force.

3.2.4 Provision of driver's demanded driving force

Figure 9 presents the data measured for a vehicle incorporating the control techniques explained in subsections 3.2.2 and 3.2.3. When the accelerator pedal was depressed rapidly, smooth driving force was obtained with excellent response; when the accelerator pedal was depressed gently, smooth, fine-tuned driving force was obtained. The data confirm that the improved shift control techniques provided the smooth, fine-tuned driving force demanded by the driver and without any lag.

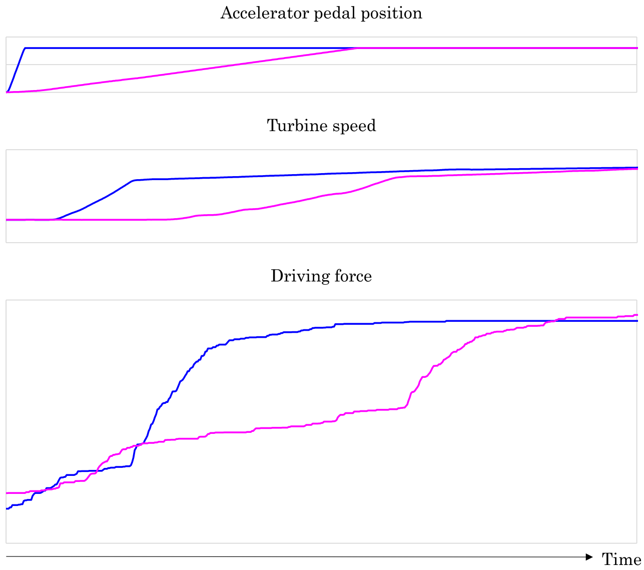

Fig. 9 Provision of driver's demanded driving force

4. Conclusion

The 9AT incorporates many control techniques that resolve the issues of increased shift busyness, worsened response and other undesirable aspects resulting from the addition of more speeds and also more fully elicits the benefits of additional speeds.

Among these techniques, this article focused on downshift control and showed how the adopted methods contribute to improving fuel economy and driveability.

In future work, we intend to develop control techniques that contribute to improving fuel economy and driveability further while also taking into account adaptation to the shift toward electrification.

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