

Analysis of CVT and Automated MT Influence on Fuel Economy, and the Estimating Improvements in Fuel Economy

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ABSTRACT

The effects on mode fuel economy by different types of transmissions, CVT and Automated Manual Transmission, were investigated using the same vehicle and engine specifications while varying transmission ratio range, friction, and similar. The results are as follows: In the case of the CVT, it was confirmed that a wider transmission ratio range is effective when driving at relatively high speeds with fewer stop-and-go situations, and friction reduction is effective when driving at relatively low speeds with frequent stop-and-go situations. On the other hand, in the case of Automated Manual Transmission, it was confirmed that a wider transmission ratio range is effective when driving at relatively high speeds with fewer stop-and-go situations, which is the same as the CVT, while a combination of a wider transmission ratio range, an increase in shift steps, and an appropriate distribution of transmission ratios is necessary when driving at relatively low speeds with frequent stop-and-to situations in order to achieve high efficiency power plant operation.

1. Introduction

In the field of transmission technology, efforts to raise fuel economy have focused not just on raising transmission efficiency but also widening the transmission ratio range with larger numbers of shift steps. One example of this is the use in a wide range of mass-market and compact cars of continuously variable transmissions (CVT), which permit a comparatively wide transmission ratio range and high thermal efficiency during engine operation. Automated manual transmissions (AMT), which have roughly the same mechanism as a manual transmission but which perform clutch operation and shifting automatically, have been widely adopted for compact buses and trucks but have seldom been used in passenger cars because of the unnaturalness drivers experience during starting and shifting. Now, however, AMT technology is once again the focus of attention as its high transmission efficiency can potentially improve fuel economy.

There are reports of research that used simulation to determine which transmission type and which specifications would improve fuel economy. However, past simulation, while using identical vehicle and engine specifications, has not been able to define transmission ratios or shift schedules with a single method, and so could not effectively compare the effects on the fuel economy of CVT and AMT. The authors, however, have presented a control system that allows the power plant (including both engine and CVT) to operate at operating points of minimum fuel consumption, along with

a computational algorithm (Gf bottom calculation) for calculating the engine and CVT operating points that achieve minimum fuel consumption⁽¹⁾⁻⁽³⁾. Applying this computational algorithm to AMT permits fuel economy simulation using the same transmission ratios and shift schedules.

This paper, using identical methods for establishing vehicle and engine specifications, transmission ratios, and shift schedules, describes the fuel economy potential of a CVT, which is slightly less efficient but which permits a wide transmission ratio range, and of an AMT, a stepped-ratio transmission that, although more efficient, has a narrower transmission ratio range, and proposes how to utilize the mechanical advantages of both to further improve fuel economy.

2. Simulation

2.1. The Conventional Approach

Simulation-based comparative research has long been carried out to determine optimum transmission type and specifications with respect to fuel economy. However, comparative research on different transmission types has employed trial and error to determine the shift schedule and transmission ratio combination, which has a major impact on fuel economy, and so could not determine whether the fuel economy achieved with the decided-on shift schedule and transmission ratio combination was the best possible fuel economy. In short, shift schedule conditions were not

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the same, and so true comparative research under identical conditions was not possible.

2.2. The Authors' Approach

The authors proposed a computational algorithm for a method of determining a shift schedule that achieves the best fuel economy for a CVT, but did not mention its application for stepped-ratio transmissions⁽¹⁾. Determining the best fuel economy for the AMT, as it is a stepped-ratio transmission, requires that the right combination of shift schedule and transmission ratio be determined. The authors therefore expanded the above-mentioned CVT shift schedule determination method, to enable the determination of the shift schedule and transmission ratio combination that results in the best fuel economy for an AMT vehicle.

Moreover, because the same algorithm is used to determine the right shift schedule and transmission ratio combination, CVT vehicles and AMT vehicles can be compared using identical conditions on the assessment axis for minimizing fuel consumption.

2.2.1. Shift Schedule

The computational algorithm for determining the best fuel economy shift schedule for a CVT vehicle is based on the following logic.

The fuel consumption (Gfuel) of a vehicle traveling at a given speed (V) and driving force (F) is expressed as the integrated value of the engine's net fuel consumption rate (BSFC), engine power (Pse), and time (Hr), with Pse expressed as the sum of the tire edge drive power (Psp) and drivetrain lost work (Psf) needed to drive at a given speed and a given driving force. This is expressed in equation (1).

$$\Sigma G_{fuel} = \Sigma \{ BSFC \times (P_{sp} + P_{sf}) \times Hr \} \quad (1)$$

The authors, seeing Gfuel, located on the left side of equation (1), as the performance function, concluded that one has only to determine the combination of BSFC and Psf that minimizes Gfuel.

Because BSFC can be changed according to throttle opening and transmission ratio and Psf according to transmission ratio and engine speed, etc. while maintaining the same engine output, the left side of equation (1) can be minimized by selecting the appropriate throttle opening and transmission ratio.

Using these computations to determine the transmission ratio for V and F for every vehicle operating point yields the shifting schedule that achieves the operating points of minimum fuel consumption.

The transmission ratio shown in Fig.1 (marked "R-AMT" in the diagram) was used in order to apply this method to stepped-ratio AMT transmissions.

If the engine and transmission operating points can be controlled according to the shift schedule that was determined with this algorithm, then minimum fuel consumption can be constantly maintained during vehicle operation.

2.2.2. Transmission Ratio Combinations

The AMT transmission ratio was determined as described below:

- The transmission ratio was determined by using the shift schedule computed as described in section 2.2.1,

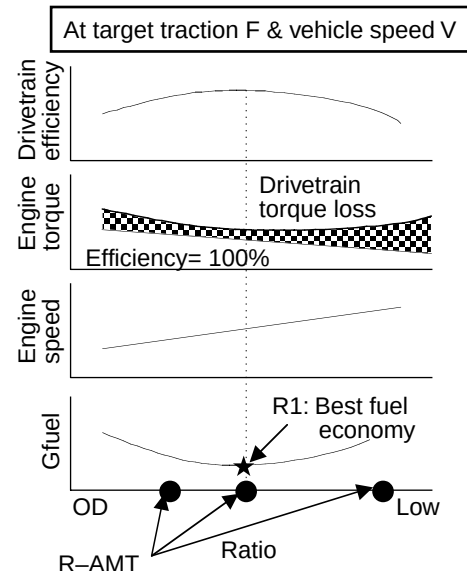


Fig.1 Gf-Bottom calculation for AMT

"Shift Schedule," to calculate, for each mode, the transmission ratio combination that produced the best mode fuel economy.

- The low ratio was defined so that the low overall ratio would be the same as that of the CVT vehicle.

The reason for doing this is to assure that the AMT vehicle has sufficient driving force at the low transmission ratio. Automatic transmission-equipped vehicles normally employ a torque converter as a starting component, while CVT vehicles employ, for example, a wet multiple disc clutch, torque converter, or electromagnetic clutch. When used as a starting component, a torque converter uses its torque amplification effect to boost starting torque, and so allows the low overall transmission ratio to be relatively small. However, when using a starting clutch or such, the absence of any torque amplification effect requires the low overall transmission ratio to be relatively high in order to assure adequate starting driving force. In a manual transmission (MT)-equipped car, which uses a dry clutch as a starting component, the driving force when starting depends on how the driver operates the clutch, i.e., a large driving force can be generated abruptly by engaging the clutch rapidly while throttling the engine. However, an AMT vehicle, because clutch operations are automatic, may not be able to deliver adequate driving force when starting with the same low transmission ratio as an ordinary MT vehicle. For this reason, the authors have assured adequate starting driving force by giving the AMT a low transmission ratio similar to a CVT's low overall transmission ratio, which was achieved by adjusting the final transmission ratio.

2.3. Fuel Economy Simulation Model

This model determines fuel consumption by first calculating the necessary driving force based on mode driving speed; then, adjusting for transmission efficiency, transmission ratio, engine accessory driving work and such, and finally determining engine speed and engine power/

torque. Fig.2 gives a block diagram of the model.

2.4. Verifying the Accuracy of the Fuel Economy Simulation Model

The model's accuracy was verified by comparing the results of simulation with data obtained during the mode driving of an actual vehicle.

Used in verification along with a CVT-equipped vehicle were the vehicle specifications listed in Tables 1 and 2. Accuracy of the model was verified by comparing the results of simulation with data obtained by measuring while driving an actual car having the same specifications as this CVT model.

Tables 1 and 2 summarize the CVT and AMT specifications used in this investigation. Both vehicles were the same model. Other than the actuator that performs shifting automatically in the AMT, there were no significant mechanical differences between the two. The conditions not

listed in the tables are as follows.

AMT conditions:

- Transmission friction was assumed to be the same as that of a 5-speed manual transmission as there is no significant mechanical difference between the AMT's power transmission system and that of a conventional MT.
- The energy needed for one shift was added to the engine work as actuator driving work.

Fig.3 shows a portion of the results for the LA4-CITY mode as an example of comparison and verification. From the top down, these are engine speed, engine torque, transmission ratio, and fuel consumption. The red and blue solid lines represent observed data and simulation data, respectively.

The difference between the observed data and simulation data for engine torque during deceleration is due to the low accuracy of the data used in simulation for negative-side

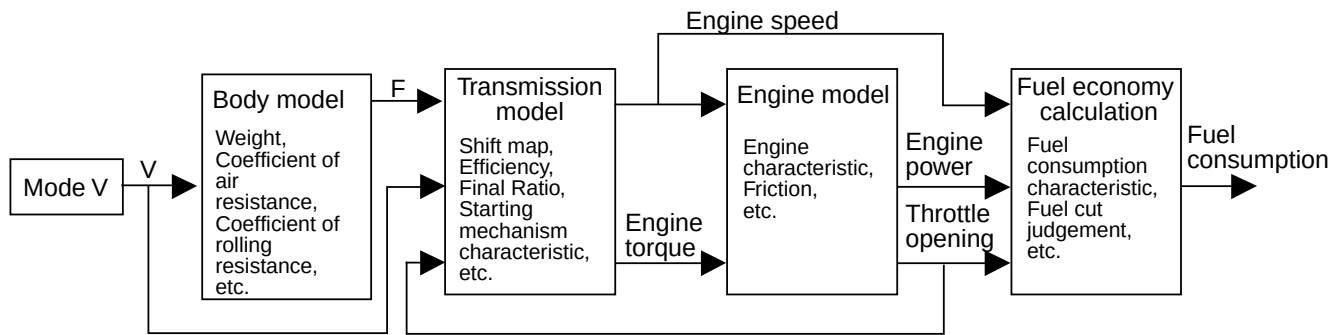


Fig.2 Simulation model structure

Table 1 Conditions of verification

Mode		US		J	
Engine	Type	1.6L 1CAM-VTEC		1.5L 1CAM-VTEC-3	
	Displacement (cc)	1590		1493	
	Horse power (kW/rpm)	85/6300		96/7000	
	Torque (Nm/rpm)	140/5400		139/5300	
Transmission	Type	Metal V-belt type CVT	Automated manual transmission	Metal V-belt type CVT	Automated manual transmission
	Starting mechanism	Wet-type multiple disc clutch	Automated clutch	Wet-type multiple disc clutch	Automated clutch
Body	Weight (kg)	1247.4	1190.7	1250	
	Tires	185/65R14		185/65R14	

Table 2 Conditions of simulation (Overall ratio)

Mode		US		J	
Transmission type		Metal V-belt type CVT	Automated manual transmission	Metal V-belt type CVT	Automated manual transmission
Overall ratio	Low	14.323	14.323	14.323	14.323
	2nd		8.382		10.145
	3rd		5.297		6.178
	4th		3.975		3.975
	5th		3.094		3.094
	Final	5.808	4.407	5.808	4.407

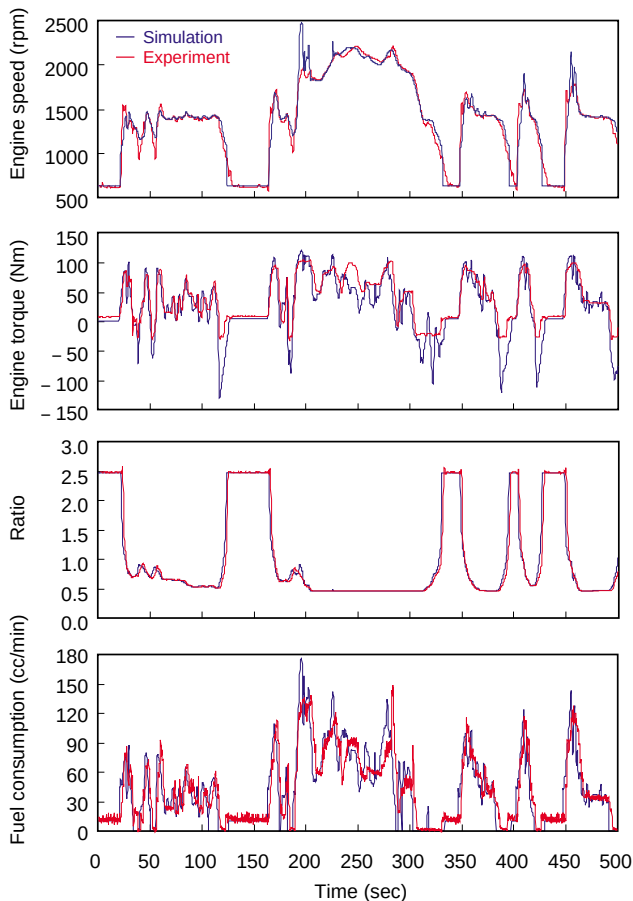


Fig.3 Result of verification
(Difference between simulation
and experiment)

engine torque. However, as this is a fuel cut (F/C) range, the low accuracy of the engine data has almost no impact on fuel economy calculations. Aside from this, sufficient correlation does exist between the observed data and simulation data for the mode.

Fig.4, which gives the mode fuel economy at this time, shows a difference of less than 2% between the observed data and simulation data. The authors therefore judged this simulation model to offer sufficient accuracy for use in the further comparison and investigation of fuel economy.

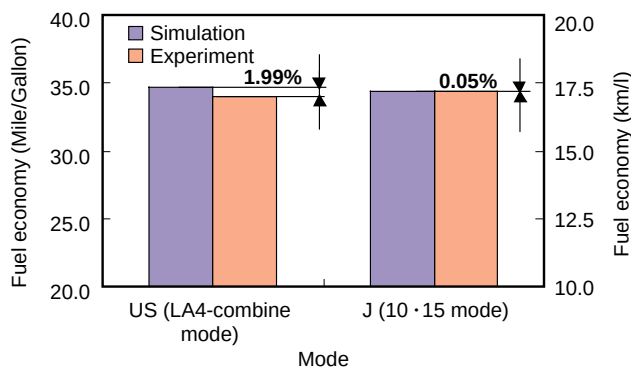


Fig.4 Mode fuel economy
(Difference between simulation
and experiment)

3. Comparing CVT and AMT Fuel Economy

This section describes the fuel economy performance of CVT- and AMT-equipped vehicles by comparing the fuel economy of the two. CVT is widely thought to permit excellent engine efficiency while the AMT provides superior transmission efficiency. In this section, the authors consider which factors promote greater fuel economy.

3.1. Specifications of the Compared Vehicles

Table 1 lists all specifications other than transmission ratio, which is given in Table 2.

3.2. Comparison of Mode Fuel Economy

The mode fuel economy for both of a CVT and an AMT was compared by simulation for the 10·15 mode and the LA4-Combine mode (“LA4-COMB”).

The results of simulation indicate that AMT yields superior fuel economy over CVT under current specifications (Fig.5).

Fig.6 gives average Pse (“Ave. Pse” in the illustration) and average BSFC (“Ave. BSFC”) during acceleration and constant-speed driving in the 10·15 mode. AMT exhibited a lower average Pse, CVT a lower average BSFC, meaning that the low-Pse AMT permits a low P_{sf} and high transmission efficiency during driving, the low-BSFC CVT permits high engine thermal efficiency. Further, another possible factor in the superior fuel economy of the AMT is that the difference in average Pse for the CVT and the AMT is larger than the difference in average BSFC.

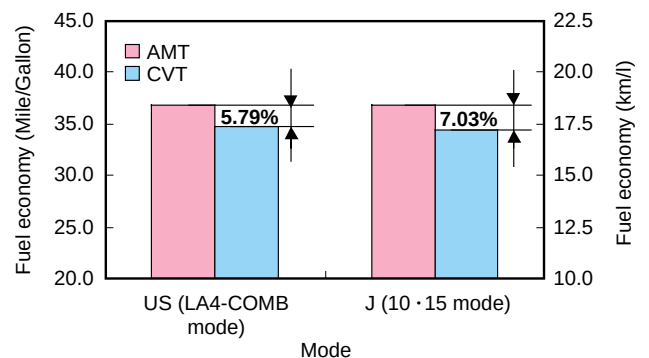


Fig.5 Fuel economy
(Difference between AMT and CVT)

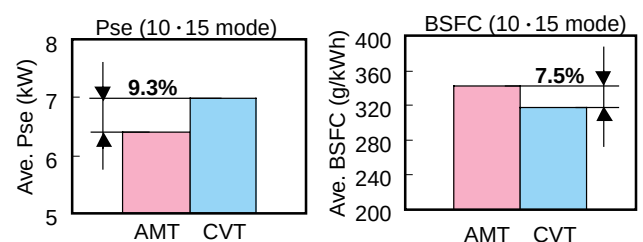


Fig.6 Average of Pse & average of BSFC
(Difference between AMT and CVT)

The graph in Fig.7 represents the relationship of engine speed to vehicle speed during acceleration and constant-speed driving in the 10·15 mode.

In the vehicle operating points there exists a range within the low-speed range that cannot be used as it used for fuel-cut and in surge prevention. Fig.7 shows how the CVT maintains a low engine speed whenever possible while avoiding this range, and how the AMT selects transmission ratios that result in low engine speeds whenever possible during constant-speed driving at 20, 40, and 50 km/h. A major difference between the CVT and the AMT is that the CVT, because of its continuously variable transmission ratio, permits complete low-engine-speed, high-load driving. In contrast, with AMT, a stepped-ratio transmission, the lowest engine speed possible at a given transmission ratio is limited to a specific vehicle speed, so that when vehicle speed rises, engine speed must also be increased until the transmission shifts to the next ratio. The result is high engine speeds coupled with low load.

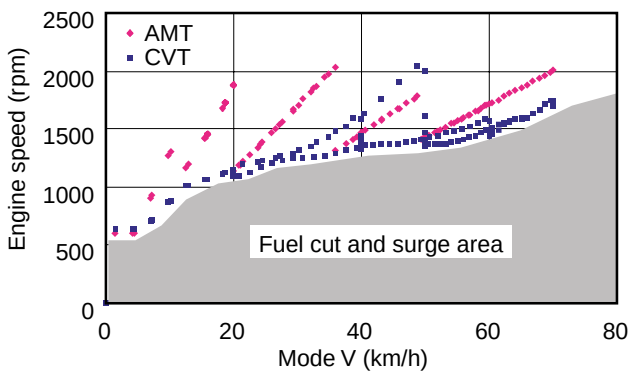


Fig.7 Comparison of engine speed
(Difference between AMT and CVT)

3.3. The Impact of Low Transmission Ratios and the Effect of Optimized Transmission Ratio Combinations

For this research, in order to have identical conditions for comparison, the AMT's final ratio was adjusted so that its low overall transmission ratio would be the same as that of CVT, the result being a large overall transmission ratio in comparison to an ordinary manual transmission. As a result, the AMT transmission ratios were less favorable with respect to fuel economy than those of the original manual transmission. For reference, the effects on fuel economy of different final ratio and optimized ratio combinations are discussed below.

These effects were investigated under the following sets of conditions.

- Mass production manual transmission ratios
- Different final ratio
- Different final ratio + optimized ratio combinations (same transmission ratios as those in Table 2)

Table 3 lists the overall ratios for each set of conditions. While Fig.8 shows the results of the investigation. The inclusion of the LA4-Highway mode ("LA4-HWY") in the LA4-COMB mode obscures the effects of transmission ratio

Table 3 Overall ratio
(Difference of final ratio & ratio combination)

Mode Conditions	US			J		
	a	b	c	a	b	c
Low	12.097	14.323	14.323	13.189	14.323	14.323
2nd	6.633	7.853	8.382	7.747	8.413	10.145
3rd	4.362	5.165	5.297	5.073	5.509	6.178
4th	3.383	4.006	3.975	3.689	4.006	3.975
5th	2.613	3.094	3.094	2.849	3.094	3.094
Final	3.722	4.407	4.407	4.058	4.407	4.407

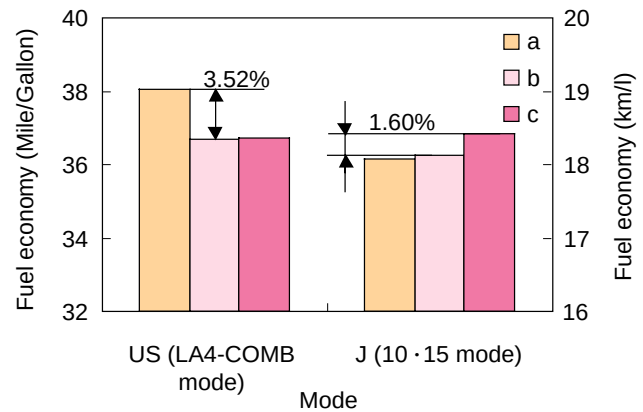


Fig.8 Fuel economy
(Difference of final ratio & ratio combination)

combination on fuel economy, and so the effect that is apparent is that of the large OD-side transmission ratio resulting from the change in final ratio.

4. Analysis of the Impact of Transmission Elements on Fuel Economy

This section considers the impact on mode fuel economy of the transmission elements of friction, transmission ratio range, and number of shift steps. By comparing these in the same modes, the authors investigated how each element contributes to mode fuel economy in CVT and AMT vehicles. The authors selected mode fuel economy as the basis of this comparison as they concluded that driving patterns with different driving loads and average vehicle speeds could be analyzed by using the 10·15 mode and LA4-CITY mode to represent driving at relatively low speeds with frequent stop-and-go situations, and the LA4-HWY mode to represent driving at relatively fast speeds with infrequent stop-and-go situations.

4.1. CVT

4.1.1. Transmission Ratio Range Impact on Fuel Economy

Here, the authors investigate the effect on fuel economy improvement of a wider transmission ratio range with smaller transmission ratios for all ratios except low, thereby achieving low-speed, high-load engine operating points and, therefore, higher engine thermal efficiency and reduced

friction.

Below are the conditions under which this investigation was performed.

Transmission ratio range: 5.0, 5.5, 6.0, 6.5

(The transmission ratio range was changed by expanding the OD-side ratio while leaving the low ratio fixed.)

Fig.9 shows the percentage of change in fuel economy for the transmission ratio range relative to the base transmission ratio range of 5.5 (the transmission ratio range of mass production CVT-equipped cars).

A 1.0 increase in the transmission ratio range resulted in a large 5.0% increase in fuel economy in the LA4-HWY mode, but a less than 1.0% improvement in the other modes. (The somewhat large 2.5% increase in the LA4-COMB mode was due to the effects of the LA4-HWY mode.)

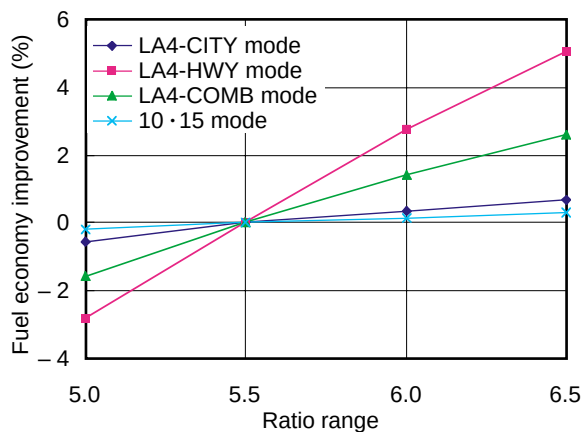


Fig.9 Fuel economy improvement of CVT (Difference of ratio range)

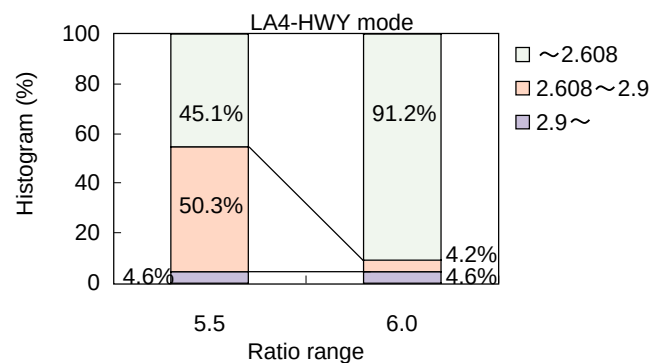
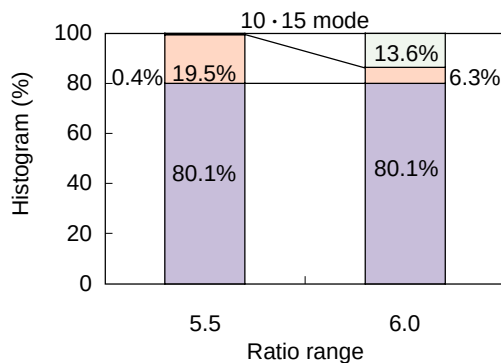


Fig.10 Ratio histogram

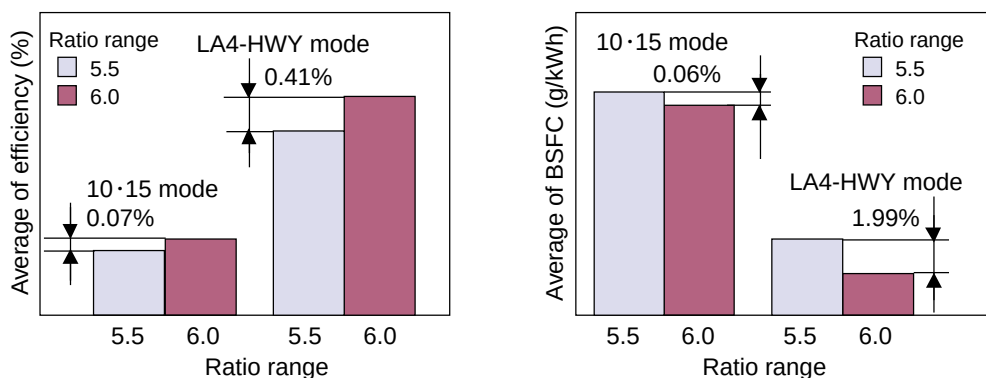


Fig.11 Average transmission efficiency & average BSFC

The results also demonstrate that in the case of the CVT, the wider transmission ratio range improved fuel economy in every mode.

Next, to determine the extent of the effect on fuel economy of low-speed, high-load driving, achieved with a wider transmission ratio range, in modes using differing driving patterns, the authors examined the 10·15 and LA4-HWY modes to compare frequency of ratio use during mode driving, average transmission efficiency, and average BSFC. The data used was collected during acceleration and constant-speed driving in each mode.

In the case of the 5.5 transmission ratio range, the graph in Fig.10 divides the range of ratio use during mode driving into 2.608 and below (the OD transmission ratio), 2.608 to 2.9, and over 2.9, and compares the frequency with which each range was used. The graph for the 10·15 mode (the left half of Fig. 10) shows that the over-2.9 range is used far more than any other, and that the 2.608-and-below range, i.e., the wider OD ratio range that accompanies the wider transmission ratio range, accounts for 13.6% of driving in that mode. In contrast, the transmission ratio range that is used far more frequently than any other in the LA4-HWY mode (the right half of Fig.10) is the under-2.608 ratio, which is used 45.1% of the time in the 5.5 transmission ratio range but 91.2% of the time in the case of the 6.0 transmission ratio range. In short, the expanded OD-side transmission ratio range is used more frequently in the LA4-HWY mode than in the 10·15 mode, meaning that in the former mode, the expanded transmission ratio range increases the frequency of low-speed, high-load engine operation.

Fig.11 compares average transmission efficiency and average BSFC in the 10·15 and LA4-HWY modes, and

shows the difference between the 5.5 and 6.0 transmission ratio ranges.

The reason for the improvement, albeit slight, in average transmission efficiency is believed to be this: With the wider transmission ratio range, the lower ratio ranges are used more frequently, and so the increase in transmission efficiency due to the lower input engine speed exceeded the drop in efficiency due to the metal belts' greater friction on the OD and low sides. The reason for the lower average BSFC is that the wider transmission ratio range resulted in a greater frequency of low-speed, high-load operation.

To summarize: In the 10·15 mode, the low frequency of low-speed, high-load engine operation translates into limited improvement of average transmission efficiency during mode driving and limited improvement in fuel economy due to the lower average BSFC, whereas in the LA4-HWY mode, the high frequency of low-speed, high-load engine operation increases improvement in fuel economy due to the lower average BSFC. This is what is responsible for the difference in fuel economy improvement in the two modes.

4.1.2. Impact on Fuel Economy of Friction Differences

This section considers the effect on fuel economy improvement of reducing friction to lower engine work.

Below are the conditions of this investigation:

Scenarios: Belt, oil pump, belt + oil pump

Rate of decrease: 0 → 100%

The reason for selecting the belt and oil pump as friction elements is that these two components together account for the majority of friction in a CVT (Fig.12).

Fig.13 shows the percentage improvement in fuel economy for different rates of friction reduction, starting from a friction reduction rate of zero.

Although there is some difference according to mode, a 0.5% improvement in fuel economy requires a roughly 5% decrease in friction in the belt-and-oil-pump scenario. In comparison to the aforementioned need for a 0.5 to 1.0 increase in transmission ratio range (0.1 in the LA4-HWY mode) to effect a 0.5% improvement in fuel economy, reducing friction is obviously an effective means of fuel economy improvement in CVT-equipped vehicles, while a wider transmission ratio range is effective when driving at relatively high speeds with less frequent stop-and-go situations.

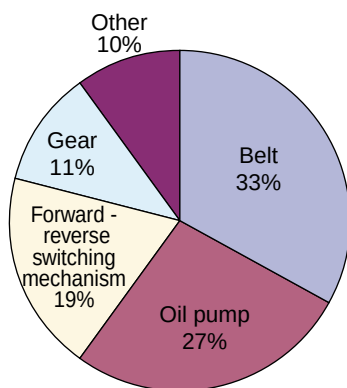


Fig.12 Power loss rate of CVT (at 40 km/h cruise)

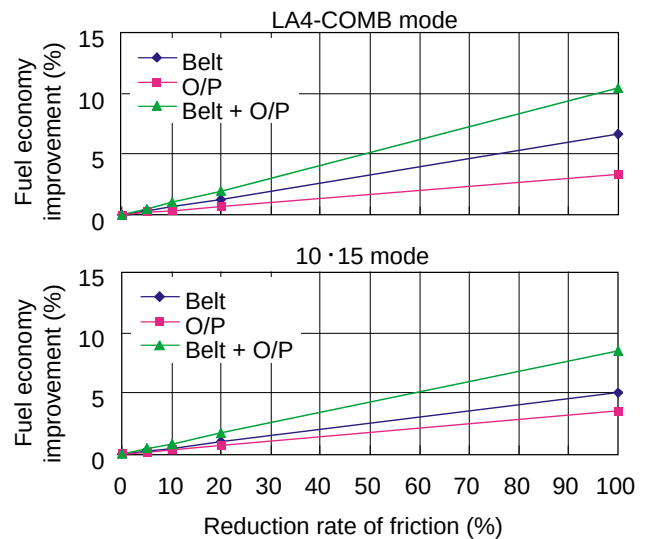


Fig.13 Fuel economy improvement of CVT (Difference of friction)

4.2. AMT

4.2.1. Transmission Ratio Range Impact on Fuel Economy

In this section, as in the case of the CVT, the authors investigate the effect on fuel economy improvement of a wider transmission ratio range with smaller transmission ratios for all ratios except low, thereby achieving low-speed, high-load engine operating points and, therefore, higher engine thermal efficiency. The effects of transmission and various friction reductions are also considered.

Whereas the CVT, being continuously variable, permits a simple widening of the transmission ratio range, the AMT requires that the proper distribution of transmission ratios be determined for the new transmission ratio range, and so the authors first sought to determine the proper distribution of transmission ratios.

The conditions used in this investigation are as follows.

Transmission ratio range: 4.6, 5.0, 5.5, 6.0

(The transmission ratio range was changed by expanding the OD-side ratio while leaving the low ratio fixed.)

Number of shift steps: 5

Fig.14 shows the percentage of changes in fuel economy for the different transmission ratio ranges relative to the base transmission ratio range of 4.6 (the transmission ratio range of mass production manual transmission-equipped cars).

As can be seen, an AMT with a wider transmission ratio range gets better fuel economy in the LA4-HWY mode but not necessarily in the other modes.

Fig.15 shows the relationship of a mode's average BSFC and average Pse to mode fuel economy at different transmission ratio ranges in the LA4-CITY mode with a low ratio that is the same as the low overall ratio of the CVT (left-hand graph) and with a low ratio that is the same as the low overall ratio of a mass production manual transmission-equipped automobile (right-hand graph).

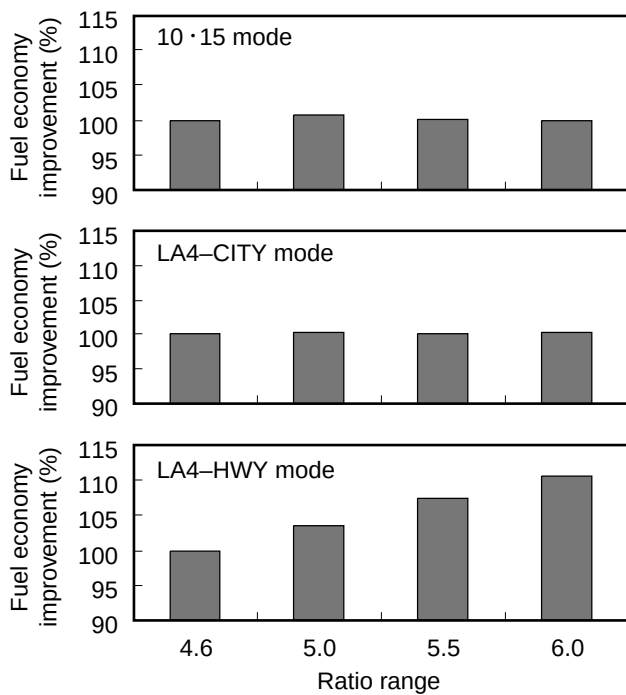


Fig.14 Fuel economy improvement of AMT (Difference of ratio range)

In Fig.15 (left-hand graph):

A transmission ratio range of 4.6 yielded the lowest average Pse, which represents engine work, but a large average BSFC, which represents engine thermal efficiency, for a resultantly low fuel economy.

There was no significant difference in average Pse among transmission ratio ranges 5.0, 5.5 and 6.0. However, the 5.5 transmission ratio range resulted in the lowest average BSFC and so the best fuel economy.

In Fig.15 (right-hand graph):

A transmission ratio range of 5.5 resulted in the lowest average BSFC but a large average Pse, and so fuel economy was poor. The 5.0 transmission ratio range yielded a large

average BSFC but the lowest average Pse and so the best fuel economy.

The preceding illustrates how exclusive focus on operating points with high engine thermal efficiency does not always improve fuel economy.

Engine work comprises the work needed for mode driving and various lost work, the latter of which depends on the transmission efficiency of the power transmission system.

This shows just how important it is to select transmission ratios and a shifting schedule that result in operating points that maximize the improvement in fuel economy when considering how to improve both engine thermal efficiency and transmission efficiency.

4.2.2. The Impact on Fuel Economy of Friction Differences

As with CVT, this section considers the effect on fuel economy improvement of reducing friction to lower engine work.

Below are the conditions of this investigation:

Rate of decrease: 0 → 100%

Transmission ratio range: 5.5

Fig.16 shows the rate of fuel economy change as related to rates of friction reduction with 0% friction reduction being base.

In descending order, the largest fuel economy change ratio for different friction reduction ratio were achieved in the modes LA4-HWY, LA4-COMB, LA4-CITY, and 10-15. Improving fuel economy by 0.5% requires a 20% reduction in friction in each mode.

4.2.3. Impact on Fuel Economy of the Number of Shift Steps

This section considers the effect on fuel economy improvement of increasing the number of shift steps to thereby increase the degree of freedom and achieve operating points with greater engine thermal efficiency.

The conditions used in this investigation are as follows.

Number of shift steps: 4, 5, 6

Transmission ratio range: 4.6, 5.0, 5.5, 6.0

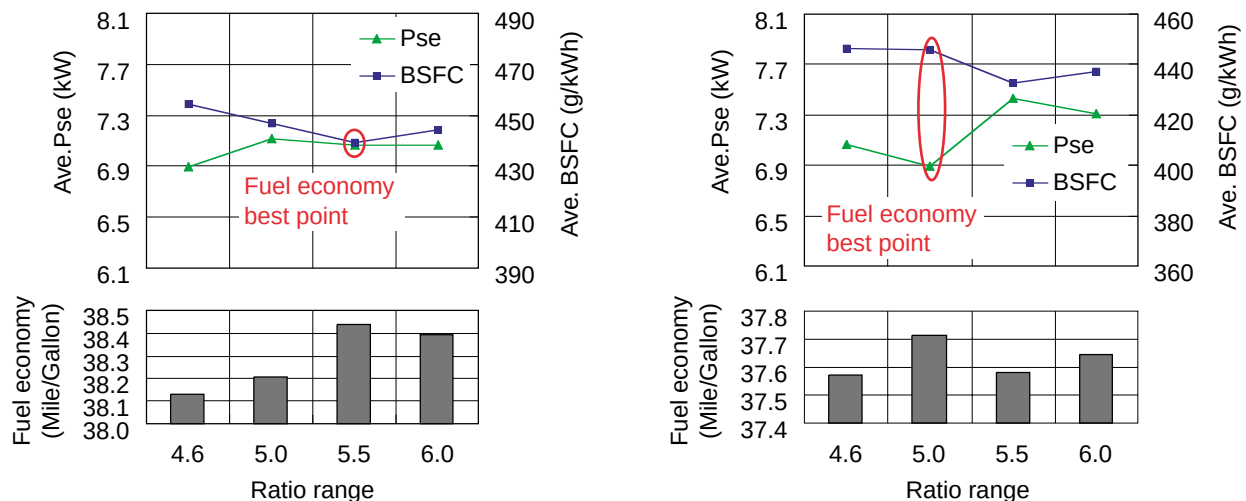


Fig.15 Relation of Pse, BSFC & fuel economy

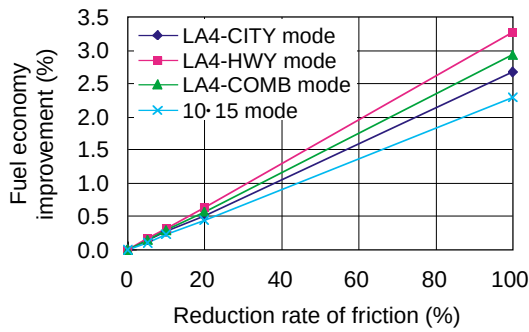


Fig.16 Fuel economy improvement of AMT (Difference of friction)

Fig.17 shows the percentage change in fuel economy for different numbers of shift steps relative to a base number of 5 steps.

Increasing the numbers of shift steps from 5 to 6 improves fuel economy by 0.5 to 1.0%. The percentage improvement in fuel economy tends to level off beyond a transmission ratio range of 6.0.

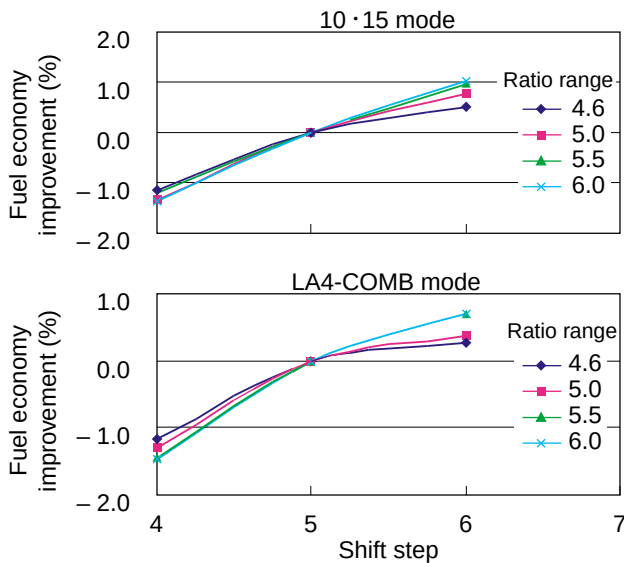


Fig.17 Fuel economy improvement of AMT (Difference between 4-speed and 6-speed)

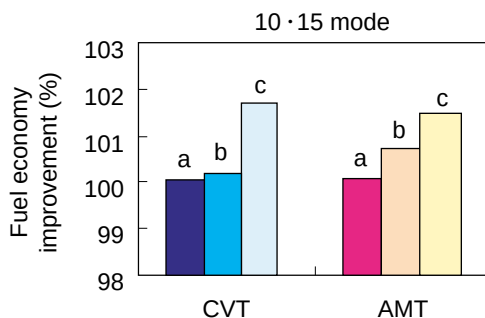


Fig.18 Simulation results under conditions of table 4

4.3. Summary of the Investigation of Fuel Economy

To summarize the preceding, friction reduction is an effective means of fuel economy improvement in the case of a CVT, as is a wider transmission ratio range when driving at high speeds, such as the LA4-HWY mode. For an AMT, friction reduction is less effective because of the already-high transmission efficiency of the AMT, for which a wider transmission ratio range is roughly as effective for high-speed driving as it is for the CVT.

In continuation of the preceding, the authors next predicted fuel economy improvements by determining what the percentage of improvement in fuel economy would be under conditions thought to be viable for both a CVT and an AMT.

Below are the sets of conditions investigated.

- Current specifications
- Wider transmission ratio range
- Wider transmission ratio range and fuel economy improvement techniques

As for the fuel economy improvement techniques, a wider transmission ratio range was used for both transmission types. In addition, friction reduction was used for the CVT, but for the AMT, a larger number of shift steps was used, as friction reduction would not significantly contribute to fuel economy improvements. The conditions are listed in Table 4.

The graph in Fig.18 shows the percentage changes in fuel economy achieved with the conditions in Table 4 relative to conditions a, which were the base conditions.

The percentage improvement in fuel economy was nearly the same for conditions a, b, and c with both the CVT and the AMT, verifying no change in the tendency of the AMT to result in better fuel economy than the CVT.

Table 4 Conditions of simulation

	Transmission type	
	CVT	AMT
a	Ratio range 5.5	Ratio range 4.6
b	Ratio range 6.0	Ratio range 5.0
c	b + Friction -20%	b + 6Speed

5. Conclusion

A simulation model permitting comparison of a CVT and an AMT according to the shift schedules that result in the best fuel economy for each was established to determine the fuel economy potential of each transmission type. By using the same technique to determine the shifting schedules for both CVT and AMT, the authors were able to compare the fuel economy of these different transmissions under more similar conditions than before.

The findings of this research are as follows:

- (1) The AMT is more advantageous than the CVT with respect to fuel economy.

Regarding further increases in fuel economy:

- (2) Reducing friction in the oil pump and belts was verified as an effective means for the CVT, as was a wider transmission ratio range for driving at high speeds, as in the LA4-HWY mode.
- (3) Friction reduction is minimally effective for the AMT, which already has a high transmission efficiency. However, a wider transmission ratio range was verified to be as effective for the type of high-speed driving typified by the LA4-HWY mode as it is for the CVT.
- (4) Essentially the same fuel economy ratio changes were achieved for both the CVT and the AMT when transmission elements were changed under conditions felt to be viable, verifying no change in the tendency of the AMT to be superior to the CVT with respect to fuel economy.

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