# Slip Control Strategy for an Automatic Transmission Vehicle

**Chinwon Lee*, Kukhyun Ahn, Jang Moo Lee**
*Seoul National University, 136-2037, Kwanak-gu, Shinlim-dong, San 56-1, Seoul 151-742, Korea*
**Won Sik Lim**
*Department of Automotive Engineering in Seoul National University of Technology,*
*Kwanak-gu, Shinlim-dong, San 56-1, Seoul 151-742, Korea*

Modern automatic transmissions equip torque converters with lock-up clutches to reduce the energy loss of hydraulic systems. Instead of simply engaging the clutch disks, the new technology of clutch slip has been developed to improve the overall efficiency of power transmission. There are two major problems with the clutch slip system. The first is how to keep the slip between the two disks within a small range and the second is when to start or stop the slip. In this paper, the second problem is discussed in view of the vehicle economy. With a simple vehicle dynamic model, the fuel economy is calculated to determine the lock-up strategy. Then the lock-up strategy is developed for a slip schedule.

**Key Words :** Clutch, Lock-up Stratege, Torque Converter, Slip Control

## Nomenclature

$C$ : Capacity factor, Nm/rad$^2$/s$^2$
$I$ : Inertia moment of rotation, kg-m$^2$
sr : Speed ratio
tr : Torque ratio
$\alpha\beta$ : Reduction gear ratio
$\omega$ : Rotational velocity, rad/s
$\phi$ : Throttle opening, %

### Subscripts

$()_e$ : Engine
$()_v$ : Vehicle
$()_c$ : Clutch
$()_p$ : Pump
$()_t$ : Turbine

## 1. Introduction

After the first oil shock in 1973, fuel economy has been an issue among automobile manufacturers. Global interests in protecting the environment also stimulated engineers to reduce the emission and the fuel consumption. To this trend, plenty of new technologies have been applied to engines, transmissions, suspensions and vehicle chassis. The "Slip control" of a lock-up clutch is one of the new technologies adopted to enhance the efficiency of an automatic transmission.

A hydraulic torque converter is an essential component in the automatic transmission. It transfers the torque from the engine smoothly to the driving wheel through a planetary gear train. Power transferred via fluid guarantees a smooth start. But the slip between a pump and a turbine causes a slip loss and hence the lower overall efficiency. Thus a lock-up clutch is used to improve the efficiency. Torque converter efficiency increases with a speed ratio until it reaches the coupling point. To avoid efficiency drop after the coupling point, the lock-up clutch is engaged. Then torque converter does not deliver power by way of fluid medium anymore. It delivers power directly as a mechanical coupling. Similarly two clutch plates can be maintained to be slipping in a small amount before there are fully engaged to each other. This technique is called "clutch slip

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* Corresponding Author,
**E-mail** : chinwon@bawi.org
**TEL** : +82-2-880-8050; **FAX** : +82-2-889-6205
Seoul National University, 136-2037, Kwanak-gu, Shinlim-dong, San 56-1, Seoul 151-742, Korea. (Manuscript **Received** May 3, 2002; **Revised** September 26, 2002)

control". Slip control may make a clutch disc carbonized easily and needs an additional hydraulic circuit, which results in a high price. Despite these disadvantages, we can get many advantages by applying slip control to the lock-up clutch. Overall fuel economy can be improved and torque fluctuations at low engine rpm can be reduced as well (Katuzmi, et al., 1996). But these improved performances are highly dependent on the control strategy.

Two key issues in clutch slip control are how and when to engage/disengage the clutch. The first problem has been studied by many researchers. Katsumi Kono, et al. (1996) analyzed how the slip amount affects the transmission efficiency and the vehicle acceleration. Moreover, they designed the hydraulic control circuit and feedback controller, which guarantees the stability in spite of the variations of various dynamic characteristics. Jiann-Shiun Lew focused on the friction uncertainty in designing the slip controller. Chinwon Lee (1998) compared performances at the converter mode, slip mode, lock-up mode in the previous works.

But no systematic procedures are proposed as to determining when to start or stop the slip control. In this paper, macroscopic control strategy is explained regarding the fuel economy. In the first section, the simple vehicle model is reviewed for a fuel economy simulation. The fuel consumption and the vehicle acceleration of two ideal vehicles are compared. One is assumed to run without lock-up. The other is assumed to run with a lock-up clutch engaged. Both vehicles are assumed to run with the same given condition. In this paper, only two parameters are used to determine the control schedule. Vehicle velocity and throttle opening are the most common system variables in determining a shift map (shift schedule chart) in conventional works. Criteria are given to determine when to start or stop lock-up with a performance result. In the next section, this method is extended to determine when to start or stop slip control. The proposed fuel criteria are optimized to get the best overall efficiency when using slip control. Finally, the range where the torque converter should be operated is discussed. This result implies the possibility of removing the one-way clutch.

## 2. System Modeling

Three ideal vehicles are considered. The first one does not use a lock-up clutch. Driving characteristics are mainly determined by engine and torque converter characteristics. The second one does not use fluid as a power transmitting medium. Entire power from the engine is delivered directly to the wheel. Driving characteristics are only determined by engine characteristics. The engine, torque converter and the clutch control input torque characterize the third one. Each vehicle is simply modeled as following Eqs. (1)-(3).

*Directly engaged vehicle*

$$I_v\dot{\omega}_v=\alpha\beta T_e-T_v \tag{1}$$

With two constitute equations $\omega_e=\alpha\beta\omega_v$, $\omega_t=\alpha\beta\omega_v$

*Converter vehicle*

$$\begin{aligned}I_e\dot{\omega}_e&=T_e-T_p\\ I_v\dot{\omega}_v&=\alpha\beta T_t-T_v\end{aligned} \tag{2}$$

With one constitute equation $\omega_t=\alpha\beta\omega_v$

*Slip controlled vehicle*

$$\begin{aligned}I_e\dot{\omega}_e&=T_e-T_p-T_c\\ I_v\dot{\omega}_v&=\alpha\beta(T_c+T_t)-T_v\end{aligned} \tag{3}$$

With one constitute equation $\omega_t=\alpha\beta\omega_v$ and external torque $T_c$

In each case, engine torque, $T_e$ is assumed to be a function of throttle opening ($\phi$) and engine speed ($\omega_e$). Here, an experimental 2D look-up table replaces nonlinear engine dynamics. The BFC (braking fuel consumption) curve is also used to calculate the fuel consumption. Figures 1 and 2 show the performance characteristics of the engine.

$$T_e=func(\omega_e, \phi) \tag{4}$$

$$T_v=func(\omega_v, grade, weight) \tag{5}$$

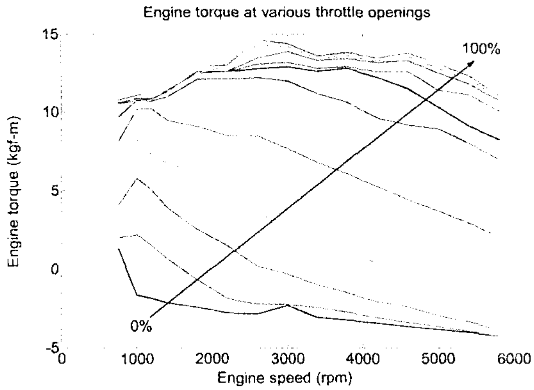

**Fig. 1** Engine torque characteristics

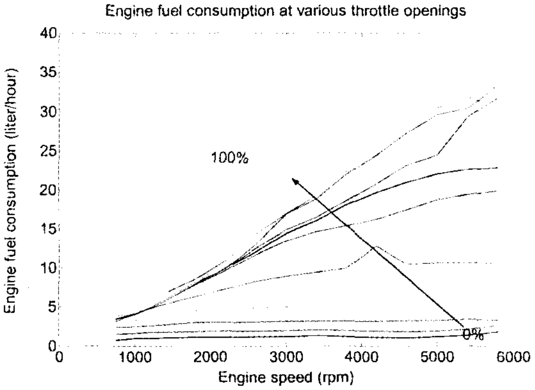

**Fig. 2** Engine fuel consumption characteristics

In a similar manner, two look-up tables replace a torque converter model. The torque ratio ($tr$) and the capacity factor ($C$) are functions of speed ratio ($sr$) and defined in Eqs. (6)-(8). Road load ($T_v$) can be modeled mathematically or experimentally. In this paper, an experimental model is used and it contains vehicel weight, air resistance coefficient and grade as decisive factors. Symbol $\alpha$ and $\beta$ represent gear ratio and final gear ratio respectively. $I_e$ and $I_v$ are the moments of inertia of engine and vehicle respectively.

$$sr=\frac{\omega_t}{\omega_p} \tag{6}$$

$$tr=\frac{T_t}{T_p}=func(sr) \tag{7}$$

$$C=\frac{\omega_p^2}{T_p}=func(sr) \tag{8}$$

If throttle opening and vehicle velocity are given, the vehicle acceleration and fuel consumption can be computed with forward-backward simulations in the following manner. Once a tire effective radius is known, wheel angular velocity ($\omega_v$) can be found. From the gear ratios, the turbine angular velocity ($\omega_t$) is also computed by constraint equations. In the directly coupled case, engine speed ($\omega_e$) is equal to turbine speed. Now fuel consumption can be calculated from engine speed and throttle opening. From Eq. (1), vehicle accelaration is also calculated. In case of the converter mode, some problems arise. There is no equation available in finding engine speed directly. This is due to the implicit form of the torque converter model. But the engine speed can be found by sweeping method, which sweeps engine speed from 750 rpm to 6500 rpm with a step size of 10 rpm to find an appropriate speed. At each engine rpm, engine torque ($T_{e1}$) is computed with the look-up table. Simultaneously engine torque ($T_{e2}$) can be computed using Eq. (7) or Eq. (8). Two engine torques, $T_{e1}$ and $T_{e2}$, which are computed seperately must be equal, if the engine speed is correctly selected. After sweeping, engine rpm is found, which minimizes the difference between $T_{e1}$ and $T_{e2}$ or $|T_{21}-T_{e2}|$. After finding engine rpm, vehicle acceleration and fuel consumption can be computed in the same way as in the directly coupled vehicle. To check the trends of the varialbes with respect to throttle opening and vehicle velocity, throttle opening is varied from 0% to 100%, and vehicle velocity is varied from 30 km/h to 180 km/h with a step size of 10 km/h.

Figures 3 and 4 show the fuel economy and vehicle acceleration for a 1.5 L passenger car. At a low vehicle speed, the lock-up mode shows a better fuel economy than the converter mode. But as the vehicle speed increases, two ideal systems show no difference in fuel economy and dynamic performances. Vehicle acceleration is also quite different at a low vehicle speed. This is because the torque converter has a characteristic of torque multiplication at a low vehicle speed. Negative acceleralation at high speed means that the vehicle cannot cruise at a high speed due to the low torque. Thus the vehicle speed will be reduced.

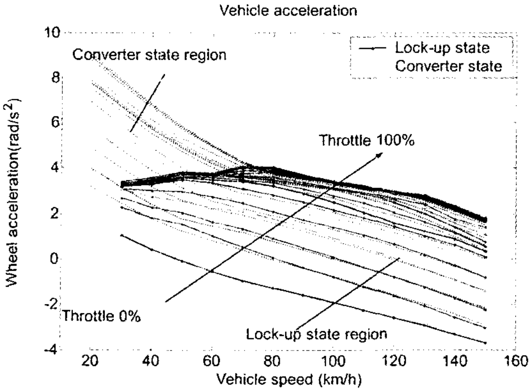

**Fig. 3** Vehicle acceleration chart with 3rd gear ratio

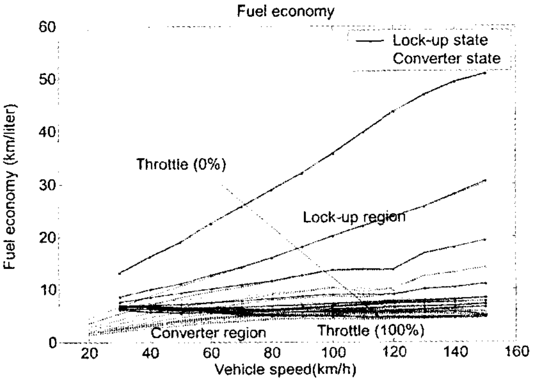

**Fig. 4** Fuel economy chart with 3rd gear ratio

## 3. Lock-Up Schedule Determination

### 3.1 Criteria candidates

- Lock-up clutch enganges/disengages at the point where the acceleration difference is zero between lock-up mode and the converter mode.
- Lock-up clutch enganges/disengages at the point where the fuel economy difference between lock-up mode and the converter mode is very small.
- Lock-up clutch enganges/disengages at the point where the speed ratio approaches to the coupling point.

### 3.2 Constraints

- The schedule chart must be made inside the assumed gear shift range.
- The schedule chart must be monotonous to prevent the chattering.

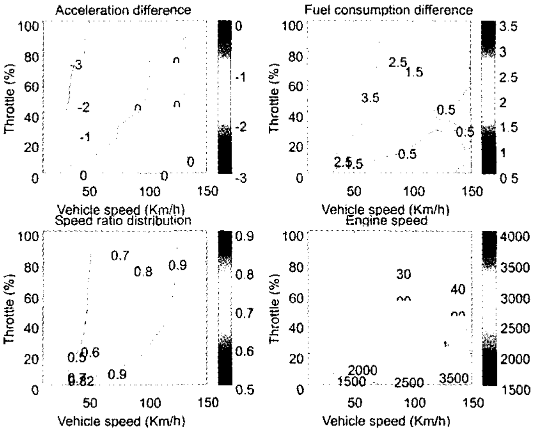

**Fig. 5** Three criteria on the 4th gear ratio

The main purpose of installing the lock-up clutch is to enchance the fuel economy in the state when the power need is not high. When the acceleration of the vehicle in the lock-up state is less than that of the vehicle in the converter state, the driver may put more fuel to get more power from the engine. Instead of widening throttle opening, disengaging the lock-up clutch make the vehicle be in the converter state where the engine torque is multiplied. Without providing additional fuel, the driver may get the required acceleration. As for fuel economy, the lock-up state is superior to the converter state. But as the fuel economy difference gets smaller, the converter mode loses its merit due to the slipping loss.

Figure 5 illustrates three lock-up criteria in the vehicle velocity versus throttle plots. The left-upper plot shows a contour lines of the acceleration difference between the lock-up mode and the converter mode. The negative value means that the converter mode has a superiority in an acceleration performance. The upper-right plot shows a contour lines of the fuel consumption difference between lock-up mode and the converter mode. Most of velocity-throttle region has positive value, which means the lock-up mode has a better fuel-economy performance. The lower-left plot shows speed ratio distribution in the converter mode. The curve when speed ratio is 0.82 is very close to the zero acceleration curve. Because the good accerelation performance is due to the torque multiplication characteristics of the torque converter, if the torque ratio is less than the unity (or speed ratio is larger than the coupling point), the converter mode loses the merit of better acceleration.

In this paper, the acceleration difference is chosen for the ENGAGE criterion and the fuel economy difference curve is chosen for the DISENGAGE criterion. Fig. 3 shows very similar lock-up schedue shape embedded in TCU (Transmission Control Unit). But exact point values are slightly different. It cannot figure out feasible points in the very low throttle opening region with proposed criteria. But practically, with small throttle opening, the torque converter needs to keep the engine on.

*Lock-up engage Condition*

*The lock-up clutch is engaged when the converter the state has no merit in acceleration performance*

*Lock-up disengage Condition*

*The lock-up clutch is disengaged when the fuel economy difference reaches the preset amount*

## 4. Algorithm to Calculate Fuel Economy

To verify the validity of this method, the backward-facing simulation program is developed, which evaluates fuel performance in a specific road cycle. General automatic vehicles can be modeled in a simple way as Eq. (9). Clutch torque ($T_c$) is zero when lock-up clutch is not engaged. When slip control is applied, clutch torque has a varying value. If the lock-up clutch is fully engaged, then two equations are combined into one, and the term regarding clutch torque vanishes.

$$\begin{aligned} I_e\dot{\omega}_e &= T_e - T_p - T_c \\ I_v\dot{\omega}_v &= \alpha\beta(T_t + T_c) - T_v \end{aligned} \tag{9}$$

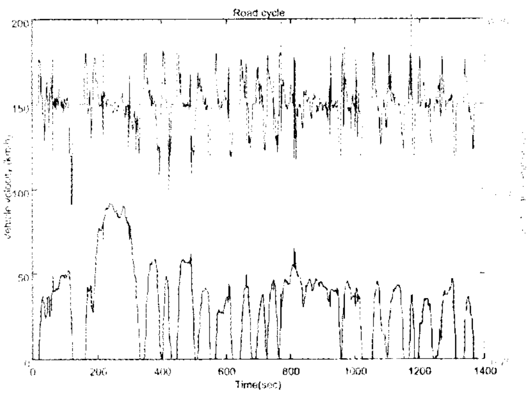

**Fig. 6** Road cycle LA city mode

In the backward simulation, the road cycle (Fig. 6) is investigated at the starting point. The wheel angular velocity, turbine velocity can be found from constitute equations given in the previous section. The required driving torque ($T_t + T_c$) at the turbine shaft can be computed from the load torque ($T_v$). Next, three cases are supposed to find the pump speed (engine speed) and required engine torque. The first case happens when a lock-up clutch is fully engaged. The second case happens when the lock-up clutch is free to move. The final case happens when the lock-up clutch is controlled. In each case, different methods are applied to find engine speed.

When the clutch is fully engaged, the required engine speed is equal to the turbine speed. The required driving torque is obtained from engine torque. When the lock-up clutch is free to move, in other word, clutch torque ($T_c$) is zero, it is not easy to find the required engine speed and engine torque, since there is no explicit model for torque converters except look-up tables with speed ratio as its parameter. The sweeping method is also available in this case. If the engine speed is assumed to be an arbitrary value, speed ratio can be calculated. From torque ratio characteristics of a torque converter, Eq. (6), the required engine torque ($T_{p1} = C(sr)\omega_e^2$) is computed. Capacity factor characteristics of a torque converter also generates the required engine torque ($T_{p2} = T_t/tr(sr)$) from Eq. (7). If the assumed engine speed is correct, two separately computed engine torque will have the same vaule. By sweeping the engine speed from 750 rpm to 6500 rpm, the speed which minimizes the difference $|T_{p1} - T_{p2}|$ is selected. The required torque is chosen to be a mean value of $T_{p1}$ and $T_{p2}$. Finally when the slip control starts, the values of turbine torque and the

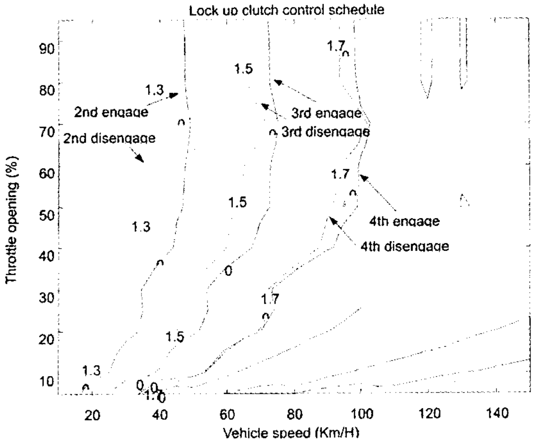

Fig. 7 Lock-up map with criteria I and II

clutch torque are obtained at the same time. If slip control is carried out succesfully, the speed difference between the engine and the turbine shaft converges quickly to the target value. Thus, the engine speed is given by Eq. (10). Eq. (9) can be rewritten as Eq. (11). Here the pump torque ($T_p$) is computed as done in the previous paragraph with the sweeping method. The required engine torque is obtained from Eq. (11).

$$\begin{aligned} \omega_e &= \omega_t + \Delta\omega_{slip} \\ T_{req} &\equiv T_t + T_t + T_c = tr(sr)\, T_p + T_c \end{aligned} \tag{10}$$

$$\begin{aligned} T_e &= T_p + T_c - I_e \frac{\omega_e(t+\Delta t - \omega_e(t))}{\Delta t} \\ &= T_{req} + (tr-1)\, T_p - I_e \frac{\omega_e(t+\Delta t) - \omega_e(t)}{\Delta t} \end{aligned} \tag{11}$$

The required engine torque should be compensated because the automotive engine torque is not only used as a tractive force but also used for the auxilliry loads such as an oil pump, an air-conditioner and so forth. After the required engine torque and speed is obtained, throttle opening demand should be calculated to find the fuel economy. Only one throttle point exists when the required engine torque and speed are given. By sweeping throttle opening from 0% up to 100%, the appropriate value can be chosen, which minimizes $|\,(T_{e,req} - func(\omega_e, \phi))\,|$.

Before starting the computation, the vehicle states such as the gear ratio, lock-up state, etc., are assumed. After the computation finishes, the values of these vehicle states are valdidated according to the shift schedule, lock-up or slip schedule. If any of the assumptions are found to be wrong, the computation is repeated.

With this program, the 1.5 L DAEWOO passenger car was investigated. With the original lock-up schedule, the program predicted fuel economy of 12.3188 Km/Liter which is very close to the experimental result, 12.3500 Km/Liter. With the new lock-up schedule in the Fig. 7, the program predicted fuel economy of 12.682 km/Liter, which is higher by around 3 percents.

## 5. Extension to Slip Control

No systematical procedure to determine the start/stop point of slip control was published yet. Some researchers try to apply slip control by shifting the lock-up schedule arbitrarily earlier. This also results in good performance improvements. But applying the criteria III proposed above in the slip schedule can make a good slip schedule.

*Slip Condition*

*The lock-up clutch slips in the region where the fuel economy difference is close to the desired value.*

In this paper, slip control starts at the curve where the fuel consumption difference is 2.5, and stops at the curve where the fuel consumption difference is 3.0. In this case the explicit design parameter is the difference of fuel economy. To get higher fuel performance, the difference should be as large as possible. But, normally high fuel economy doesn't go along with low acceleration performance. Generally high fuel economy strategy results in very early slip-control schedule. But too early slip schedule may cause a clutch damage, a control failure, excessive control efforts, and the reduction of dynamic performances. The slip control should satisfy the heat capacity constraint equation, Eq. (12).

$$P = \int_{\omega 1}^{\omega 2} T_c d\omega \leq P_{design} \tag{12}$$

where, $\omega_1$ is the starting point of slip control, and

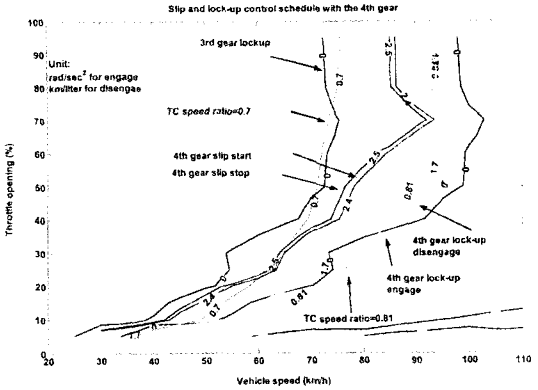

**Fig. 8** Slip and lock-up control schedule on the 4th gear ratio

$\omega_2$ is the starting point of lock-up.

Figure 8 shows the contour line where the speed ratio is 0.81. The region left to this line exploits the merit of torque multiplication while the opposite side does not. This result implies that the torque converter is not operated in the high speed ratio region. The conventional torque converter adopts a one-way clutch to improve the efficiency in the high-speed region. But the slip control with proposed slip control schedule enables the one-way clutch to be removed in the torque converter. This may reduce a large amount of costs in the torque converter production.

## 6. Conclusion

From above discussions, followings can be induced and fuel consumptions are summarized in Table 1 with lock-up and slip control strategies.

(1) The systematical procedure for scheduling the lock-up clutch is proposed. The procedure is based on the vehicle acceleration and the fuel economy. The proposed method shows the same fuel economy performance as the old lock-up map. We can conclude that the old map is composed so that the vehicle shows the optimal fuel economy performance.

(2) The systematical procedure for scheduling the slip control is also proposed, which predicts about 3% improvement in the fuel economy. The proposed method is based only on the fuel economy of the vehicle.

**Table 1** Validation of proposed method

| | Experiment with embedded map | Simulation with TCU embedded lock-up schedule | Simulation with proposed lock-up schedule | Simulation with proposed slip control schedule |
|---|---|---|---|---|
| Fuel economy (Km/Liter) | 12.35 | 12.31 | 12.32 | 12.68 |

(3) The backward-facing simulation program to find a fuel economy is made and validated by experimental results.

(4) The automatic transmission with a properly designed lock-up/slip control strategy does not need a torque converter with a one-way clutch. This may reduce large amount of manufacturing costs.

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