POWER DISTRIBUTION CONTROL ALGORITHM FOR FUEL ECONOMY OPTIMIZATION OF 48V MILD HYBRID VEHICLE

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ABSTRACT
In this paper, we developed a supervisory control algorithm for fuel economy optimization of 48V MHEV (Mild Hybrid Electric Vehicle). It consists of the driving mode decision algorithm (Driving modes of 48V MHEV: Idle stop & go, EV(EV-launch, sailing), HEV(torque assist, Charge), ICE only, Recuperation) and power distribution algorithm for each driving mode. In particular, power distribution control is a key factor in determining the fuel economy of 48V MHEV. In this paper, a simulation-based analysis is performed to analyze the fuel consumption relevance of the power distribution algorithm. The vehicle model was developed in the Autonomie environment. The optimal power distribution control method was derived by analyzing the fuel consumption simulation results (traveling cycle: FTP 75) for the power distribution control with different tendencies.

Key Words : 48V mild hybrid electric vehicle, Supervisory control, Power distribution control

1. INTRODUCTION
In recent years, OEMs have been working to develop xEVs such as electric vehicles, hybrid electric vehicles, and fuel-cell electric vehicles in accordance with the global fuel economy and CO2 regulations. However, high-voltage, environmentally-friendly vehicles have not satisfied consumers because of the high cost of the vehicle to meet safety requirements. Solving these problems, OEM adopts the 48V system and develops the Mild Hybrid system which has better fuel economy improvement rate. This method can minimize powertrain structural changes, which can reduce the complexity of the vehicle system and reduce the cost. Various configurations (P0 ~ P4) have been proposed according to the electric motor mounting method of the 48V mild hybrid system (Figure 1).

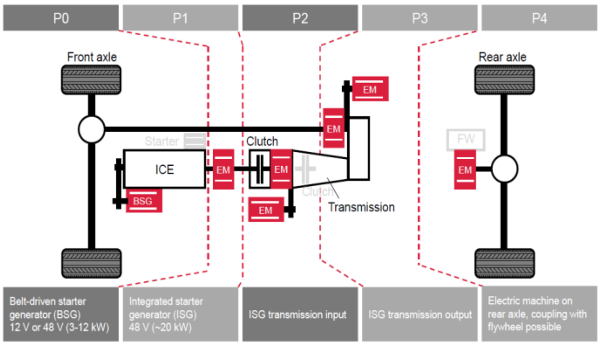

Figure 1: Configuration according to motor position

The P0 configuration replaces the existing belt-driven 12V generator to achieve a 48V system with minimal cost, while the P1 to the P4 configurations can be equipped with a high power motor with high mechanical power transfer efficiency. In addition, the P2-P4 configurations are capable of running in the EV mode, so the fuel efficiency improvement is high. The P4 configuration has the similar shape of e-AWD so that the vehicle dynamics control function can be realized.

In this paper, we study the P0 + P4 mixed configuration. This configuration enables various operations ranging from idle stop & go, EV mode, regenerative braking, charge, and torque assist to high efficiency through the combined operation of the belt drive generator (BSG) and the rear-axle drive motor. Among these supervisory control functions, the tendency of power distribution between regenerative braking, charging and torque assist is a key factor in determining fuel economy improvement. In this paper, we propose a rule - based power distribution algorithm for optimal fuel economy by analyzing the effect of each control on fuel economy. For this purpose, a 48V mild hybrid vehicle model with P0 + P4 configuration is realized using Autonomie and a simulation case for power distribution control with different tendencies is defined. Finally, we derived a rule-based power distribution control method optimized for 48V mild hybrid system through fuel economy simulation in FTP-75 cycle.

2. VEHICLE MODEL AND SIMULATION ENVIRONMENT

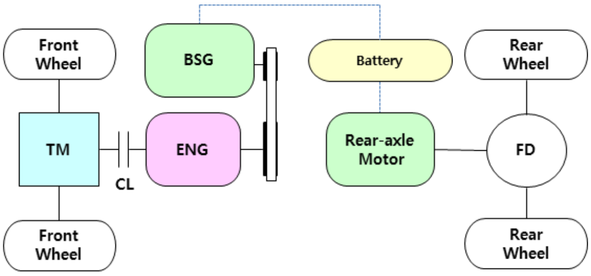

Figure 2: Target Vehicle

As shown in Figure 2, a 48V MHEV vehicle with a P0 + P4 structure is modeled. TM is the transmission, CL is the clutch, ENG is the engine, and FD is the final drive. The front wheel can be driven by the engine and the BSG, and the engine and the BSG are connected by a belt, which allows the torque assist and engine start via the BSG. The rear wheel is driven by a rear-axle motor. The main components information of the target vehicle are shown in Table 1.

Table 1: Vehicle main components

Engine	99kW L gasoline engine
BSG	11kW PM motor
Rear-axle motor	10kW PM motor
Battery	48V/11.5Ah lithium-ion battery

The 48V mild hybrid vehicle with the configuration as shown in the Figure 3 is the composition of the simulation model. The simulation model developed using Autonomie is consists of an upper controller, a driver model, an environmental model, and a powertrain model. Powertrain components consist of an engine, BSG, rear-axle motor, 48V and 12V battery, BDC, LDC, wheel, vehicle dynamics model, etc.

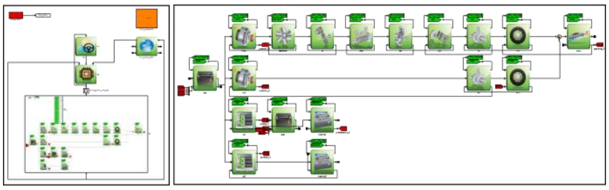
Figure 3: Simulation model and powertrain configuration

Table 2: Vehicle Parameters

Vehicle weight (kg)	1490
Frontal Area (m^2)	2.8
Rolling Coefficient	0.009
Aerodynamic Coefficient	0.37
Air density (kg/m^3)	1.23
Front final drive ratio	4.113
Rear final drive ratio	10.74

3. SUPERVISORY CONTROL ALGORITHM

As shown in the figure 4, the upper control algorithm was developed using Simulink, and consists of the mode decision algorithm and the power distribution algorithm of each mode.

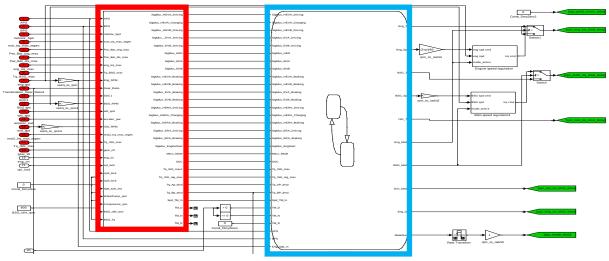
Figure 4:Supervisory control algorithm(Power distribution(red)/Mode decision(blue) algorithm)

3.1. Mode decision algorithm

In the mode decision algorithm, the driving mode is determined according to the driver's request and the vehicle state. The driving modes used in the 48V MHEV are classified as follows.

1. Idle stop & go mode
   In this mode, the engine is turned off at stop to save idle fuel consumption. Since it starts by using BSG, it can operate when the SOC is above a certain level.

2. EV mode
   In this mode, when the driver's acceleration demand torque is below the EV limit torque and the SOC is above a certain level, the vehicle travels using the rear-axle motor. It is used to start with a low demand torque when the vehicle is stationary, or to maintain the vehicle speed while driving.

3. ICE only mode
   In this mode, the vehicle is driven by the engine only when the driver's acceleration demand torque exceeds the assist limit torque or the torque assist of the motor is limited due to low SOC.

4. HEV torque assist mode
   In this mode, the vehicle travels to the engine and the motors when the SOC is above a certain level and the acceleration demand torque is above the EV limit torque and below the Assist limit torque.

5. HEV charge mode
   In this mode, when the charge sustaining is not possible with only recuperation energy, charge using engine and BSG. It is also used to prevent battery over discharge.

6. Recuperation mode

This mode is used to convert the kinetic energy of the vehicle into electrical energy when the deceleration demand torque is occurring.

Table 3: Driving mode according to driver's demand torque

Driver torque demand	Driving mode	
$T_{dmd} > T_{assist\_lim}$	ICE	Charge
$T_{assist\_lim} \geq T_{dmd} > T_{EV\_lim}$	Torque assist	
$T_{dmd} \leq T_{EV\_lim}$	EV	
$T_{dmd} < 0$	Recuperation	

T_{dmd} is the driver demand torque in the engine shaft, T_{assist_lim} is the control parameter that limits the torque assist torque to below the corresponding value. T_{EV_lim} is the control parameter that limits the EV mode to operate below the corresponding value with the EV limit torque.

3.2. Power distribution algorithm

In the power distribution algorithm, the torque command for each part such as engine, BSG and rear-axle motor is calculated for each mode according to the driver's request.

1. ICE only mode
   In this mode, the torque demand is distributed only to the engine. The power distribution formula is as follows.

$$T_{eng} = T_{dmd} \quad where\ T_{dmd} > T_{assist\_limit}$$
$$T_{mot} = 0 \qquad (1)$$
$$T_{BSG} = 0$$

where T_{mot} is the rear-axle motor torque, T_{dmd} is the driver demand torque, T_{eng} is the engine torque, T_{BSG} is the BSG torque, T_{assist_limit} is the assist limit torque.

2. EV mode
   In the EV mode, the demand power is satisfied only by the rear-axle motor. The EV limit torque can also be determined.

$$T_{mot} = \frac{R_{tm} \cdot R_{front}}{R_{rear}} \cdot T_{dmd} \quad where\ T_{dmd} \leq T_{EV\_limit}$$
$$T_{eng} = 0 \qquad (2)$$
$$T_{BSG} = 0$$

where T_{EV_limit} is the EV limit torque. R_{rear} is the rear final drive ratio, R_{front} is the front final drive ratio, R_{tm} is the gear ratio of transmission.

3. HEV torque assist mode
   In HEV assist mode, the torque for each of the engine, BSG, and rear-axle motor is calculated according to the demand torque. The assist limit torque can also be determined. The torque compensation amount of the motors can be controlled through the control variable f (T). Assist limit torque becomes 0 (f (T)).

$$T_{mot} = \min\left(f(T) \cdot T_{mot\_max}(w), \frac{R_{tm} \cdot R_{front}}{R_{rear}} \cdot T_{dmd}\right)$$
$$T_{BSG} = \min\left(f(T) \cdot T_{BSG\_max}(w), (T_{dmd} - \frac{R_{rear} \cdot T_{mot}}{R_{tm} \cdot R_{front}}) \cdot \frac{1}{R_{pulley}}\right)$$
$$T_{eng} = T_{dmd} - T_{mot} - T_{BSG} \qquad (3)$$
$$where\ T_{assist\_limit} \geq T_{dmd} > T_{EV}$$

where $T_{mot\_max}(w)$ is the rear-axle motor maximum torque , $T_{BSG\_max}(w)$ is the BSG maximum torque, R_{pulley} is the belt pulley ratio, $f(T)$ is the control variable for power distribution of motors.

The EV / HEV drive domain is determined by the EV / HEV assist limit torque. Through this, the electric energy consumption of the battery is controlled to perform charge sustaining. Therefore, it is possible to control the use of all the charged electric energy to make a reliable fuel consumption comparison.

4. HEV charge mode
   In this mode, the engine torque is output by adding the torque to be charged to the BSG to the driver's requested torque.

$$T_{BSG} = T_{BSG\_gen\_min}(w)$$
$$T_{eng} = T_{dmd} + T_{BSG} \cdot R_{pulley}$$
$$T_{mot} = 0 \qquad (4)$$

where $T_{BSG\_gen\_min}(w)$ is the minimum generating torque of BSG.

5. Recuperation mode
   In Recuperation mode, the torque is distributed to each motor according to the braking torque demand. If the braking torque demand exceeding the maximum regenerative braking torque, the friction brake is used. In this way, distributing the motor torque firstly, the regenerative braking energy can be maximized.

$$T_{mot} = \max\left(T_{mot\_reg\_min}(w), \frac{R_{tm} \cdot R_{front}}{R_{rear}} \cdot T_{dmd}\right)$$

$$T_{eng} = 0 \quad (5)$$

$$T_{BSG} = \max\left(T_{BSG\_reg\_min}(w), (T_{dmd} - \frac{R_{rear} \cdot T_{mot}}{R_{tm} \cdot R_{front}}) \cdot \frac{1}{R_{pulley}}\right)$$

$$where\ T_{dmd} < 0$$

where $T_{mot\_reg\_min}(\omega)$ is the minimum regenerating torque of rear-axle motor, $T_{BSG\_reg\_min}(\omega)$ is the minimum regenerating torque of BSG.

4. SIMULATION

In some cases, the simulation was performed by applying the host controller developed in the simulation model.

4.1. Simulation case

As shown in the table 2, different simulation cases are defined as follows.

Table 4: Simulation case according to driving mode

Simulation case	Driving mode
A	Idle stop & go
B	A + Recuperation
C	B + Torque assist
D	C + EV
E	D + Charge

1. Case A
   Only idle stop & go mode is performed, it is a criteria to determine the degree in improvement of fuel economy.

2. Case B
   Perform only idle stop & go / recuperation mode. It is possible to estimate the electric energy that can be obtained in the driving cycle.

3. Case C
   All electrical energy obtained through regenerative braking is used to perform torque assist mode.

4. Case D
   Set the EV limit torque to the maximum torque of the rear-axle motor to maximize the EV mode and use the extra regenerative energy for torque assist.

5. Case E
   The EV mode is maximized and the extra regenerative energy and forced charged energy are used as torque assist.

4.2. Simulation result

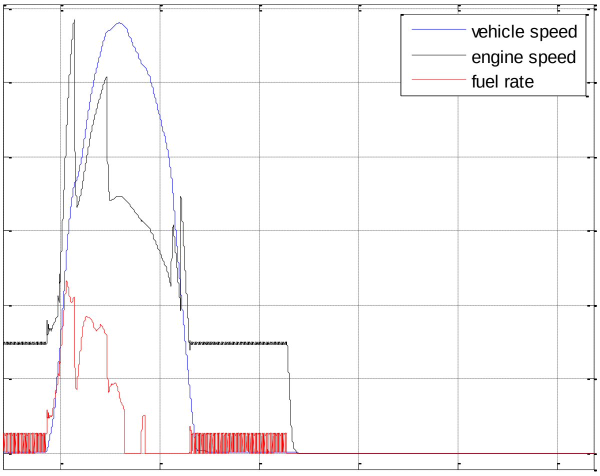

Figure 5: Simulation result of Case A

This is an enlarged view of a part of the simulation result. Each value is scaled for easy viewing because of the scale difference. Idle stop & go The engine keeps idle for a certain period of time after the vehicle is stopped, and the engine is turned off and the fuel consumption is zero. This confirms that idle top & go operation reduces unnecessary fuel consumption.

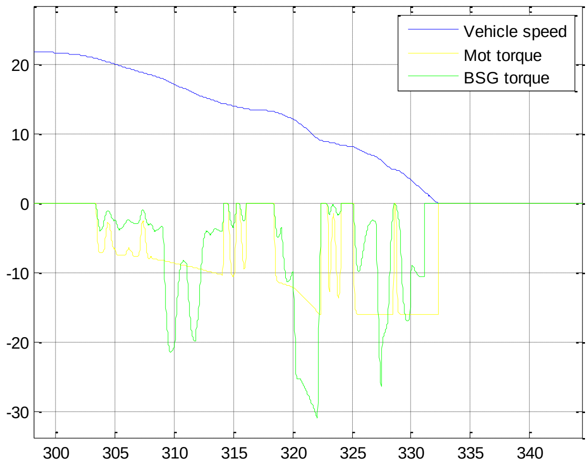

Figure 6: Simulation result of Case B

In the above graph, regenerative braking using two motors can be confirmed when decelerating. It is also possible to confirm that the torque is distributed preferentially to the rear-axle motor.

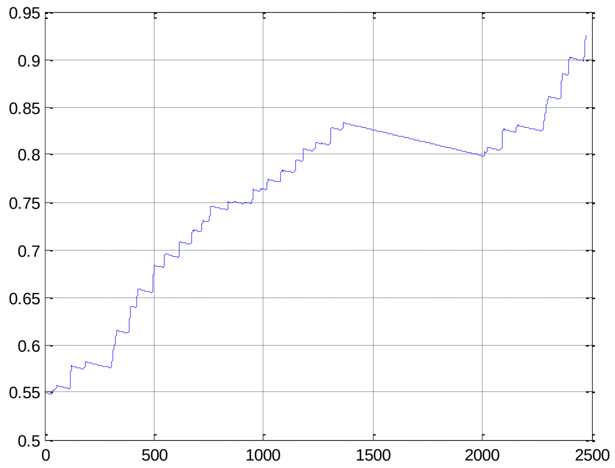

Figure 7: SOC of Case B

In the above graph, it can be confirmed that the battery SOC is increased by regenerative braking. It can be confirmed that the initial SOC is 55% and the final SOC is 92.56%, except for the power consumption by the electric component. It is charged 37.56% by regenerative braking, and this energy is used for torque assist and EV mode.

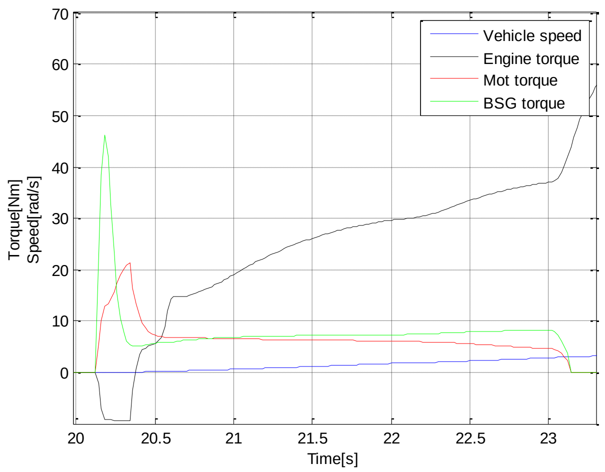

Figure 8: Simulation result of Case C

This is the beginning of the case. Torque assist mode starts from about 20.5 seconds and ends in about 23 seconds. As shown in the graph above, the energy obtained by regenerative braking is consumed through the torque assist of the motor. In the following figure, it can be confirmed that the starting SOC is equal to the final SOC.

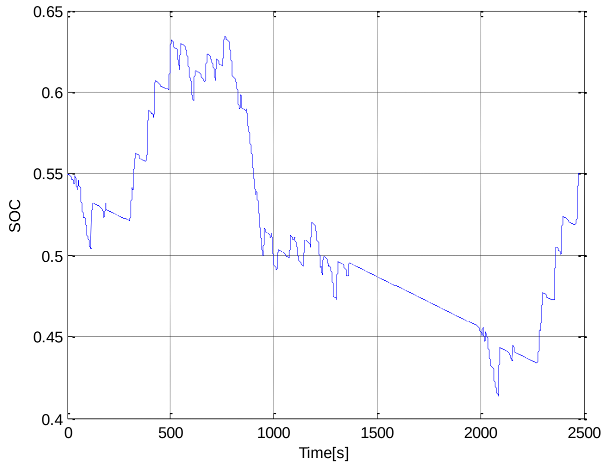

Figure 9: SOC of Case C

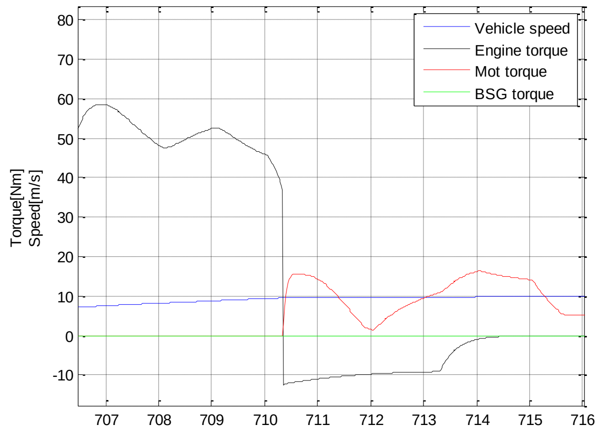

Figure 10: Simulation result of Case D

In the above graph, EV mode starts from about 710.5 seconds. The regenerative braking energy is consumed through the EV mode and the SOC is maintained in the running cycle as shown below.

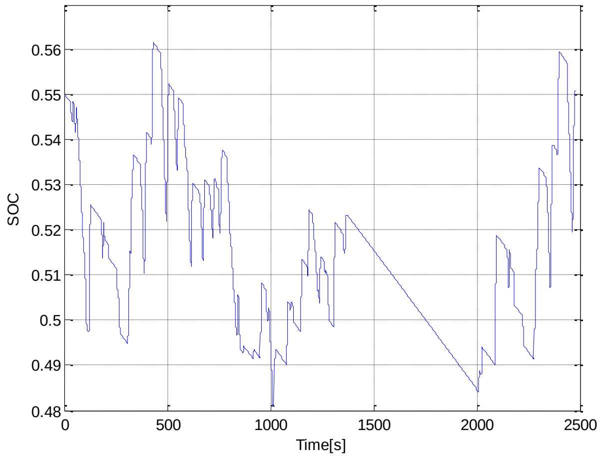

Figure 11: SOC of Case D

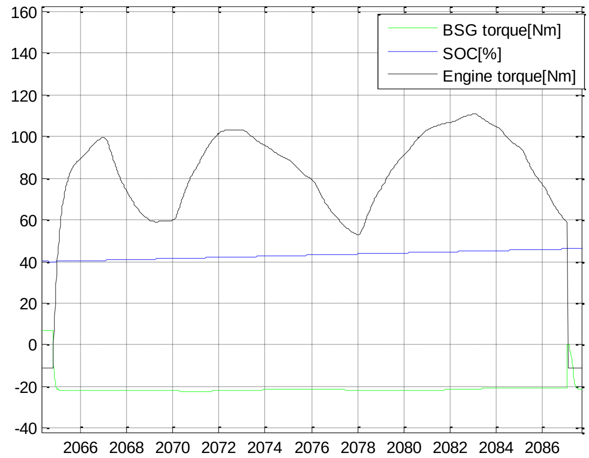

Figure 12: Simulation result of Case E

In the figure 12, it can be seen that the forced charge is working because the SOC drops to less than 40%.

The fuel economy of each simulation case for the driving cycle (FTP 75) is as follows.

Table 5: Fuel economy results

Simulation case	Driving mode	Fuel economy
A	Idle stop & go	14.48
B	A + Recuperation	14.73
C	B + Torque assist	17.03
D	C + EV	18.75
E	D + Charge	18.31

Comparing cases C and D, it can be seen that the EV mode is more effective in improving the fuel economy than the torque assist mode when the regenerative braking energy is the same and the total energy charged in battery is used. While both cases of D and E use EV mode to the maximum, but in the case E, additional torque assist is performed using the electrical energy obtained by the forced charging, which is inefficient. In the C and E cases, Comparing C and E cases, Even if the fuel is used for charging, it can be seen that the fuel efficiency is improved by using the EV mode.

5. CONCLUSION

The fuel economy improvement between C, D and E cases is determined by EV use domain and the torque to assist ratio of the BSG and the rear-axle motor. Among them, the EV mode domain contributes the most to fuel efficiency improvement. At presented results, the best fuel economy is shown in case D, but the more detailed study is needed to determine the control tendency to obtain optimum fuel efficiency.

ACKNOWLEDGMENTS

This work was supported by the Industrial Strategic technology development program, 10076437, Development of hybrid drive topology exploration and control technology for fuel economy optimization of 48V mild HEVs funded By the Ministry of Trade, industry & Energy(MI, Korea).
This research was supported by BK21 Plus project of the National Research Foundation of Korea Grant.

REFERENCES

Bao, R., Avila, V., and Baxter, J., “Effect of 48V Mild Hybrid System Layout on Powertrain System Efficiency and Its Potential of Fuel Economy Improvement,” SAE Technical Paper 2017-01-1175, 2017.

German, J. “Hybrid vehicles: Trends in technology development and cost reduction,” ICCT, http://www.theicct.org/hybrid-vehicles-trends-technology-development-and-cost-reduction, 2015.

Kuypers, M., "Application of 48 Volt for Mild Hybrid Vehicles and High Power Loads," SAE Technical Paper 2014-01-1790, 2014.

Dixon, G., Steffen, T., and Stobart, R., "A Parallel Hybrid Drive System for Small Vehicles: Architecture and Control Systems," SAE Technical Paper 2016-01-1170, 2016.

Brown, A., Nalbach, M., Kahnt, S., and Korner, A., "CO2 Emissions Reduction via 48V Active Engine-Off Coasting," SAE Int. J. Alt. Power. 5(1):2016.

Kuypers, M., "Application of 48 Volt for Mild Hybrid Vehicles and High Power Loads," SAE Technical Paper2014-01-1790, 2014, doi:10.4271/2014-01-1790.

Kim, S., Park, J., Hong, J., Lee, M. et al., "Transient Control Strategy of Hybrid Electric Vehicle during Mode Change," SAE Technical Paper 2009-01-0228, 2009, doi:10.4271/2009-01-0228.

Piccolo, A., Ippolito, L., Vaccaro, A., 2001. Optimisation of energy flow management in hybrid electric vehicles via genetic algorithms. IEEE/ASME International Conference on Advanced Intelligent Mechatronics Proceedings. Vol.1, pp.434–439.