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Calculation of Fuel Consumption on Hybrid Power System Driven by Two Motors Connected in Series with CVT

Koji SAKOTA, Kazuya OKUBO, Toru FUJII

Abstract— **This study discussed configuration of driving system for improving power efficiency of hybrid electric vehicle driven by two motors connected in series with CVT (Continuously Variable Transmission). In the system, the driving power was supplied by two motors in which one had large ability in power generation compared with that of another one. Algebraic simulation was executed to determine the shear ratio of the power by each motor with a simple model which referred information on the torque property curve of each motor. In the simulation, it was supposed that mechanical power was produced only by two motors but reciprocal engine in the system, in which the engine contributed to supply electric power to the motors. Nominal capabilities of motors used in this study were 10, 20, 30kw, respectively. Two motors were selected among them in which total motor power was to be 30, 40, or 50kw for the system in each condition. An effective parameter (Emt) was defined as the threshold of applied torque by sub-motor to determine the minimum condition where auxiliary power was supplied by the sub-motor beyond the condition. In the two motors system, the revolution speed of the sub-motor was controlled to be constant at 150rad/s by the CVT with metal V-belt to maintain high efficiency of the sub-motor. Calculation results of current system were compared with that of traditional system driven by single motor. The difference of energy consumption was also calculated according to the difference of driven modes.**

In some conditions, energy consumption often decreased when double-motor system was applied. However, simply designed double motor system was not always effective to reduce the energy consumption to drive the vehicle. When the CVT was applied to double motor system, energy consumption was decreased compared with those by simply double and single motor system both for the acceleration up to low and high speed. Lowest energy consumption was observed on the double motor system controlled with CVT, when the 30Nm of the (Emt) was set on the sub-motor. Improvement of 6 % in fuel consumption should be obtained in case of the "10 mode" in which vehicles were often driven under low speed mode.

Index Terms— Hybrid Electric Vehicle, Motor, CVT, fuel consumption, Algebraic simulation

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I. Introduction

Hybrid electric vehicle was focused as one of new types of automobiles in not only Japan but also in world wide scale. The hybrid electric vehicle is defined as a new type vehicle in which more than two different energy sources was combined such as engine and motor [1], [2]. It is often or always available that energy consumption is reduced when the motor and engine are corroborated to drive the vehicle [3], [4].

However, enough effect is not obtained in current hybrid driving system compared with ideally expected one. It is considered that one of reason of the problem is due to single motor system.

This study, at first, discussed an advantage of double motor system for improving power efficiency of hybrid electric vehicle. In the system, the driving power was supplied by two motors in which one had large ability in power generation compared with that of another one. In the simulation, mechanical power was supplied only by the two motors, but reciprocal engine in the system, where the engine contributed to supply electric power to the motors and battery. For further improvement of the system, the CVT was applied to control the revolution numbers of the sub-motor, as discussed later.

Algebraic simulation was executed to determine the shear ratio of the power by each motor with a simple model which referred information on the torque property curve of each motor. Nominal capabilities of motors used in this study were 10, 20, 30kw respectively. Two motors were selected among them in which total motor power was to be 30, 40, or 50kw for the system in each condition. An effective parameter (Emt) was defined as the threshold of applied torque by sub-motor to determine the minimum condition where auxiliary power was supplied by the sub-motor beyond the condition. Calculation results of current system were compared with that of the traditional system driven by the single motor. The difference of fuel consumption was also calculated according to the difference of driven modes.

II. METHOD OF SIMULATION

A. *Configuration of hybrid system*

Figure 1 shows the basic configuration of hybrid system discussed in this study. The hybrid system was consisted of reduction gear, main-motor (EM1), sub- motor (EM2), engine, power controller and battery. It was supposed that a double-motor system was prepared for the driving system discussed in this study. At first, acceleration was assisted by

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the sub-motor for start from rest. In the system, total torque was applied only by main motor when the driving speed was low, while the corporation by two motors was often achieved to drive the system.

If the SOC (state of charge) of battery was decreased below the specific threshold, the battery was charged by sub-motor. This operation was priority to over other actions. Figure 2 shows the modified configuration of hybrid system proposed in this study. In the modified system, CVT was utilized to keep constant revolution numbers of the sub-motor when the sub-motor contributed to assist the system.

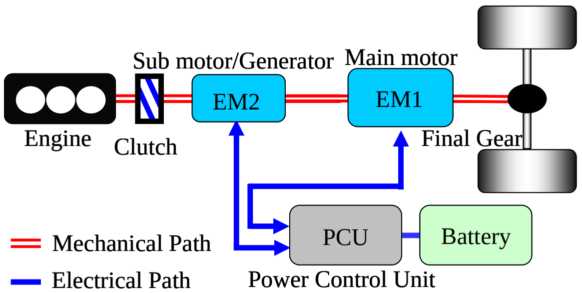


Figure 1 Schematic view of double motor hybrid system

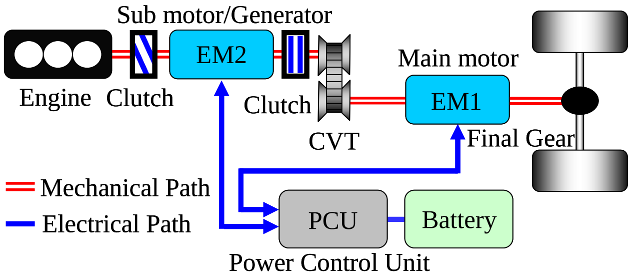


Figure 2 Schematic view of double motor hybrid system with CVT

B. Calculation of driving energy

The energy consumption of the driving system was calculated as below.

$$P_{req} = F_t(t)v(t) \qquad (1)$$

The travel resistance was shown as equation (2) which was sum of the reaction resistance of inertia, air, rolling and gradient at slope, respectively [5]. Table 1 shows parameters of the calculation model. All parameters were determined to calculate usual conditions for a compact sedan car.

$$F_t(t) = m_v \dot{v}(t) + 0.5\rho_a c_d A_f v^2(t) + c_r m_v g + m_v g \sin(\alpha) \qquad (2)$$

Table 1 Parameters of calculation model

Mass vehicle	m_v	1400	[kg]
Rolling coefficient	c_r	0.015	[−]
Aerodynamic coefficient	c_d	0.30	[−]
Frontal area	A_f	2.0	[m^2]
Ratio of final drive	r_{fd}	3.5	[−]
Density air	ρ_a	1.18	[kg/m^3]
Gravitational acceleration	g	9.81	[m/s^2]

C. Simulation process

Figure 3 and 4 show the MATLAB-Simulink models [6] - [8] for the simulation of basic hybrid system and modified hybrid system with CVT, respectively, shown in the section II -A. The vehicle speed and the acceleration at the arbitrary driving mode was output from the calculation block. The vehicle speed and acceleration at each driving mode was output from the calculation block. The energy consumption was calculated considering arbitrary reduction ratio, revolution number of motor and torque. The fuel consumption was estimated by converting the required energy.

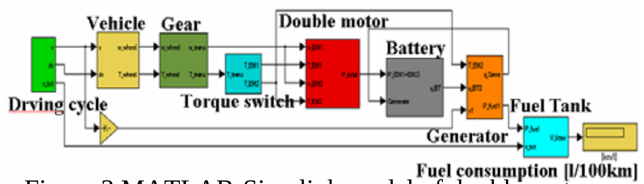


Figure 3 MATLAB-Simulink model of double motor hybrid system

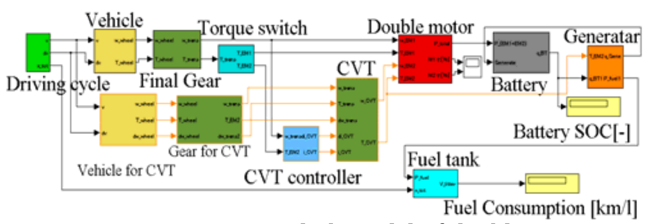


Figure 4 MATLAB-Simulink model of double motor hybrid system with CVT

III. RESULT AND DISCUSSION

A. Double motor system

Figure 5 shows change of energy consumption for the start of vehicle from rest to 80km/h of speed. This graph indicated that the vehicle required large driving power at acceleration behind constant speed condition. Figure 6 shows the difference of required motor power to keep constant 80km/h of speed of the vehicle, according to the motor size defined as the capacity of motor power. If small power motor was selected, required total power was decreased to keep the constant speed. Figure 7 (a), (b) show the contours map of the efficiency curve of the 50kw motor and 10kw motor determined at the conditions of motor toque and speed, respectively. The circles in the graph indicated calculated data of motor efficiency at the constant speed condition (80km/h). High efficiency was also calculated if the system was driven by small power motor.

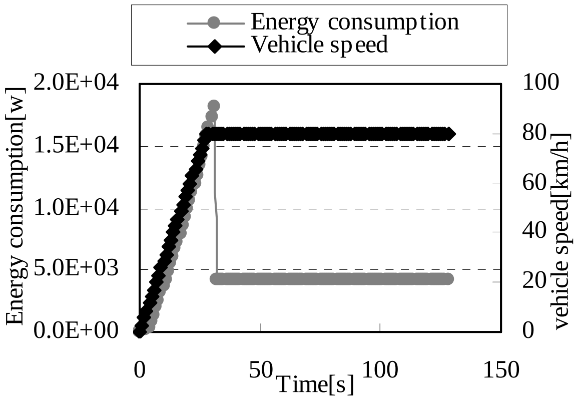


Figure 5 Energy consumption with vehicle speed

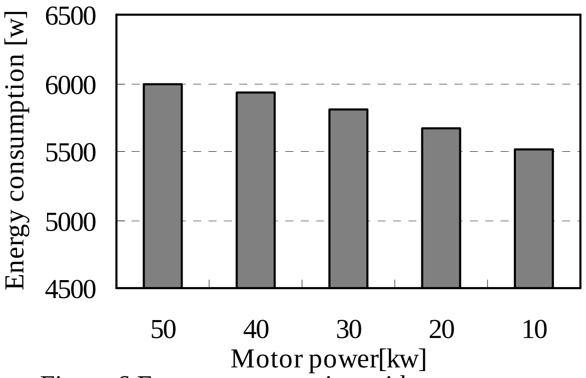
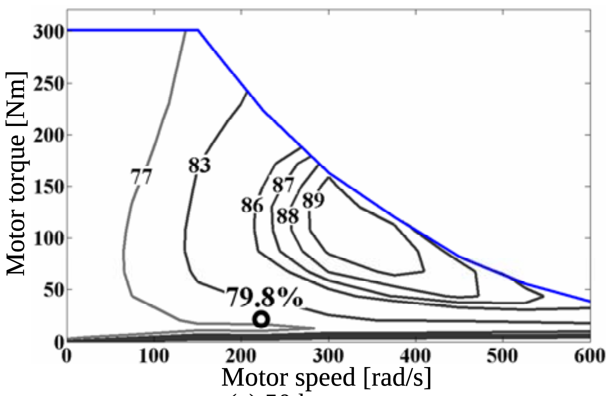
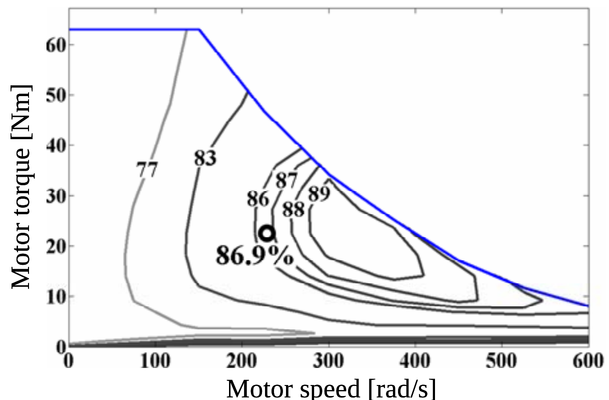


Figure 6 Energy consumption with motor power at constant 80km/h of speed



(a) 50 kw motor



(b) 10 kw motor

Figure 7 Contours map of the efficiency curve of motor

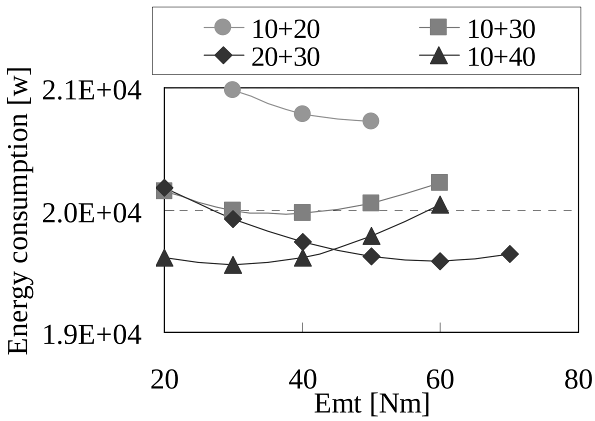
B. Energy consumption of double motor system

To improve the power efficiency of the motor drive, at first, simply parallel motors system was tested. The driving power was supplied by two motors in which one had large ability in power generation compared with that of another one, in the parallel motors system. In this paper, the parallel motors system was simply called as "double motor system". The nominal capabilities of motors used in this study were 10, 20, 30kw, respectively. Two motors were selected among them in which total motor power was to be 30, 40, or 50kw as shown in Table 2.

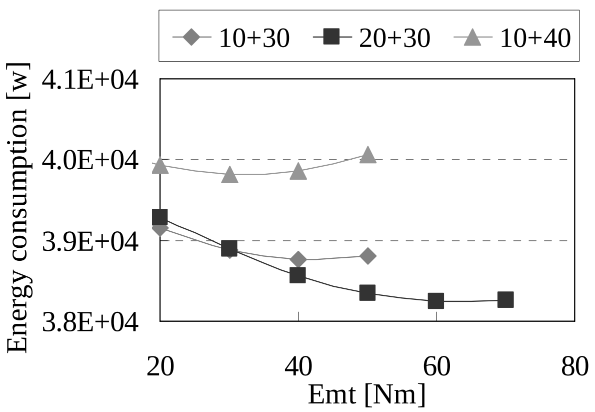
In the simulation, energy consumptions under two modes were calculated, in which the vehicle was supposed to be accelerated to 40 and 80km/h of the speeds, respectively, from rest under 0.79m/s^2 of acceleration. An effective parameter (Emt) was defined as the threshold of applied torque by sub-motor to determine the minimum condition where auxiliary power was supplied by the sub-motor beyond the condition. Figure 8 (a), (b) show the change of energy consumption of the double motor system with respect to Emt for the acceleration up to low and high speed (rest to 40 and 80km/h), respectively. When the 10＋40kw and 20＋30kw motors were selected for the double motor system, low energy consumption was observed in acceleration up to low speed. Even for acceleration up to high speed (rest to 80km/h) the energy consumption was also decreased when 20＋30kw motors were selected.

Table 2 Total motor power

Total power[kw]	Main+Sub[kw]
30	10 + 20
40	10 + 30
50	20 + 30 10＋40



(a) Rest to 40km/h



(b) Rest to 80km/h

Figure 8 Change of energy consumption with respect to Emt

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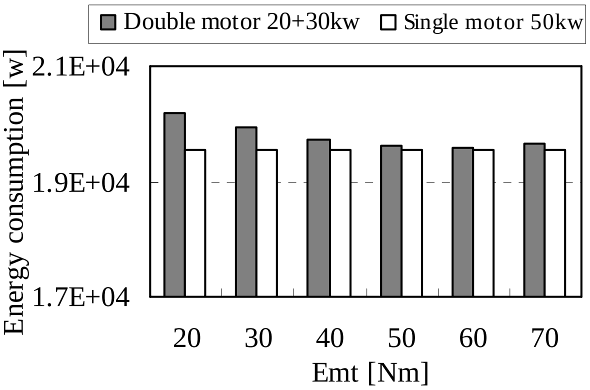
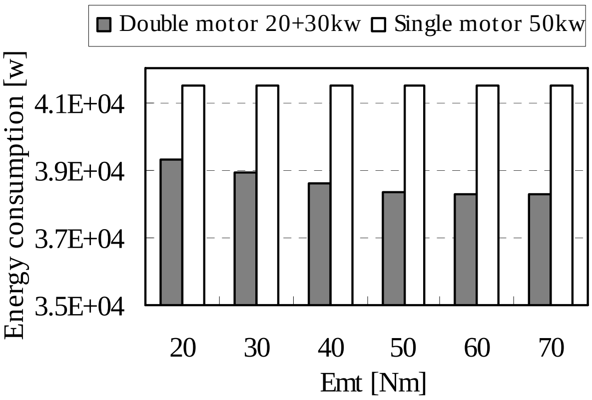
The energy consumption was changed by setting the parameter of (Emt) at acceleration. Figure 9 (a), (b) show the comparison of energy consumption of double motor system with that of single motor system, when the system was accelerated up to 40 and 80km/h, respectively. For acceleration up to high speed, double motor system was effective for decreasing the energy consumption. However, double motor system consumed large energy for acceleration up to low speed. It was found that simply designed double motor system was not always effective to reduce the energy consumption to drive the vehicle.



(a) Rest to 40km/h

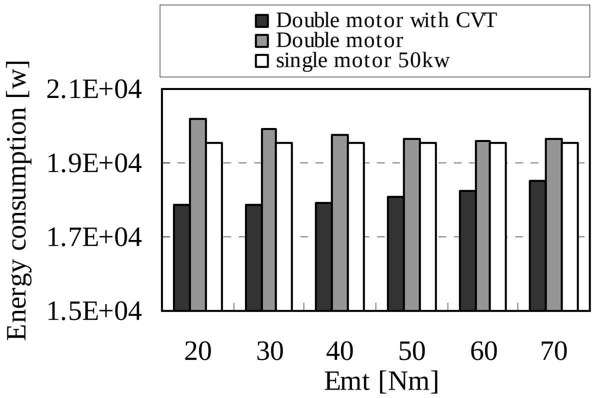


(b) Rest to 80km/h

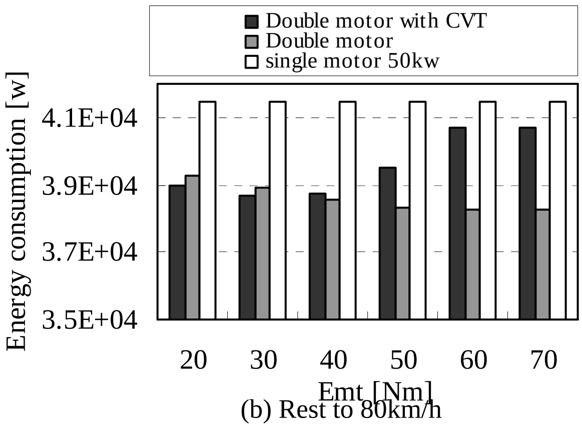
Figure 9 Comparison of energy consumption of double motor system with single motor system

C. *Effective of CVT*

One of idea to reduce the energy consumption is to keep high revolution numbers of the motors. In this study CVT was utilized on the double motor system mentioned above, to control the number of revolutions of the sub-motor. In order to set the revolution of sub-motor at 150rad/s, the reduction ratio of the CVT was operated to the low side. Operating low reduction ratio of the CVT, the revolution numbers of sub-motor was kept by the CVT, where independent high efficiency of the sub-motor was expected due to the property. Figure 10 (a), (b) show the difference of the energy consumptions of the systems discussed in this study, for the acceleration up to 40 and 80km/h from the rest, respectively.



(a) Rest to 40km/h



(b) Rest to 80km/h

Figure 10 Comparison of energy consumption between double motor system, double motor system with CVT and single motor system

When the CVT was applied to the system, the energy consumption was decreased compared with other simply double and single motor system both for accelerations up to low and high speed. Especially, among all conditions, lowest energy consumption was observed when the 30Nm of the Emt was set on the sub-motor.

D. *Difference of energy consumptions according to driving mode*

Using the double motor system which is consisted of 50kw (20+30kw) motor, the fuel consumption was calculated on three types of driving mode. Figure 11 shows the driving mode patterns of 10mode, 10-15mode and test mode which was used on the simulation. The “test mode” was defined as the specific driving patterns to describe a practical driving data urban for ten minutes in Japan. Each driving mode was repeated until total 260km of the driving distance was achieved. Figure 12 (a) – (c) show the difference of fuel consumptions according to driving mode when the initial SOC (state of charge) was changed. The fuel consumption with gasoline was estimated in which equivalent energy was assumed to drive the system. In the high speed driving modes like the 10-15mode and the test-drive mode, double motor system was not effective to improve fuel consumption compared with that by the single motor system. Remarkable improvement of 6% in fuel consumption should be obtained in case of the “10 mode” in which vehicles were often driven under low speed mode. It was suggested that the double

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motor system with CVT was effective aspect to reduce the fuel consumption of vehicles.

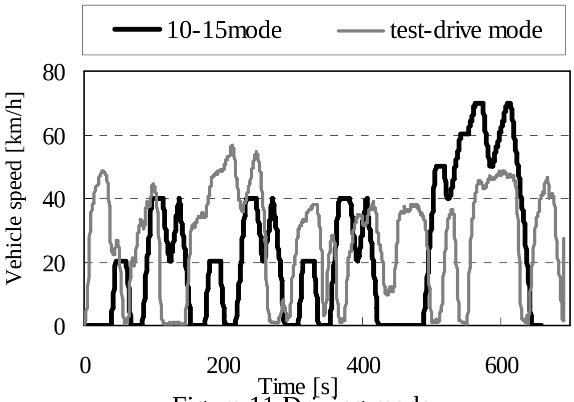
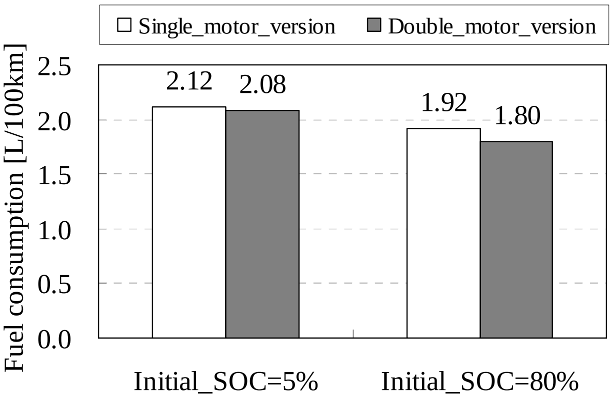
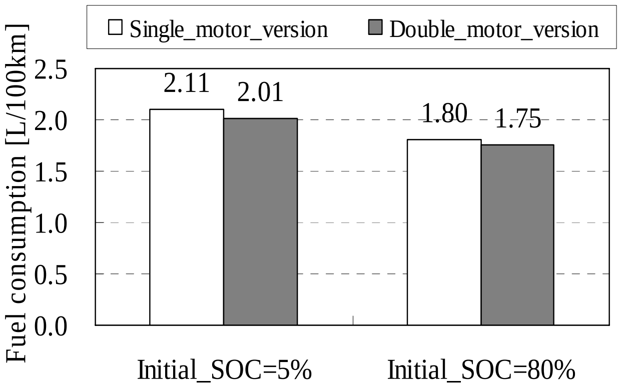


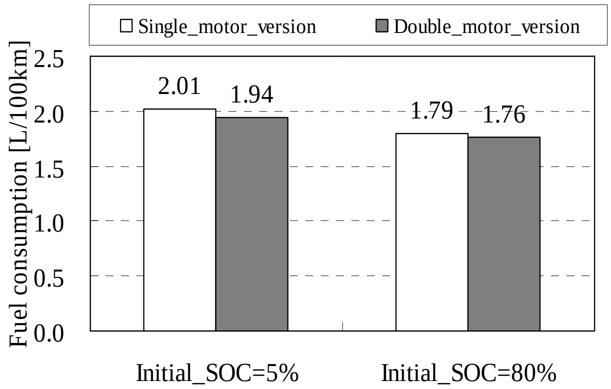
Figure 11 Driving mode



(a) 10mode



(b) 10-15mode



(c) testdrive mode

Figure 12 Fuel consumption

IV. CONCLUSION

1) Simply designed double motor system was not always effective to reduce the energy consumption to drive the vehicle.
2) When the CVT was applied to double motor system to keep constant revolution numbers of sub-motor, energy consumption was decreased compared with those by simply double and single motor system both for the acceleration up to low and high speed.
3) Lowest energy consumption was observed on the double motor system controlled with CVT, when the 30Nm of the (Emt) was set on the sub-motor.
4) Improvement of 6% in fuel consumption should be obtained in case of the “10 mode” in which vehicles were often driven under low speed mode.

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