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Estimation of the Power Requirement of Twin-Seater Ultra Compact Vehicles and their Environmental Impact, for the Japanese Market

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Abstract

Twin-seater ultra compact vehicles have attracted much attention. This is because the twin seater configuration provides the minimum cabin space required for commuter use and contributes to reduce energy consumption for travel due to their light weight in comparison to regular sized passenger vehicles. In Japan, the average number of passengers in a vehicle used for daily activities is 1.3 people. Therefore, the currently prevalent motor vehicles may be over-sized for daily use, and two-seater vehicles may be more appropriate to satisfy the demands of Japanese in their daily activities. The Japanese government is considering the introduction of a new category for such vehicles. The size of ultra compact vehicles should not be larger than the K-car (light car) standard and not be smaller than the existing mini-car standard in Japan. In this study, the power requirement for twin-seater ultra compact vehicles was estimated in order to obtain basic data for the development of this new vehicle category. In addition, their environmental impact, which includes reduction of energy consumption and greenhouse gas emissions, was evaluated. Advantages of the introduction of these vehicles into the Japanese market also are discussed.

Keywords: energy consumption, EV, ICE, NEV, power

1 Introduction

The reduction of propulsion energy of vehicles can reduce the consumption of fossil fuel and consequently reduce the emission of greenhouse gas. Reducing the weight of vehicles is the key to reduction of propulsion energy.

The average number of passengers of a vehicle used for daily activities in Japan is 1.3 people. Nevertheless, ordinary-sized motor vehicles have much larger capacity, generally 4 to 5 seats. Therefore, the usual motor vehicles may be over-sized for daily use, and two-seater vehicles may be a more appropriate means to satisfy the demands of Japanese daily life. Two-seater vehicles are much lighter than regular sized passenger vehicles, whose weight is about 1,000 kg, and are expected to require less propulsion energy.

Mini-cars that are defined in Japanese rules and regulations have only one seat, and the rated power of the vehicles is limited to 0.6 kW. Mini-cars with this specification can meet the demands of only a limited range of activities, such as parcel delivery service, and they cannot be an alternative to regular sized passenger vehicles. Therefore, a new type category of mini-cars that has two seats is desired.

With the above as background, the Japanese government is now considering whether a new vehicle category (tentative name: Ultra compact vehicle (UCV)) for vehicles which have two seats and are smaller and lighter than the K-car should be created in order to introduce such vehicles in the market.

As the first step in development of this new vehicle category, this study aims to clarify the power requirement of the UCV motor so that safe and smooth driving can be achieved while still substantially reducing energy consumption and greenhouse gas emissions in comparison to existing vehicles. In addition, advantages in initial and running costs of such a motor are discussed.

2 Calculation method

2.1 Calculation model

In order to calculate the motor power output that is required for UCVs to perform safe and smooth driving, the energy consumption involved in driving such a vehicle and its greenhouse gas (CO_2) emissions, it is necessary to solve the equations of motion of a vehicle, setting provisional specifications such as the vehicle weight and driving mode. The components of force acting on a UCV on a slope are shown in Figure 1.

The power output necessary for propelling a vehicle, P (W), is:

$$P = F \cdot dx/dt = F \cdot V \tag{2.1}$$

where

$$F = R_r + R_l + R_s + R_a$$

$$R_r = \mu_r \cdot m \cdot g \cdot \cos\theta$$

$$R_l = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot V^2$$

$$R_s = m \cdot g \cdot \sin\theta$$

$$R_a = (m + \Delta m) \cdot \alpha$$

F stands for driving force (N), R_r stands for rolling resistance (N), R_l stands for air resistance (N), R_s stands for grade resistance (N), R_a stands for acceleration resistance (N), V stands for vehicle speed (m/s), μ_r stands for rolling resistance coefficient, m stands for vehicle weight (kg), g stands for gravitational acceleration (m/s^2), θ stands for gradient (rad), ρ

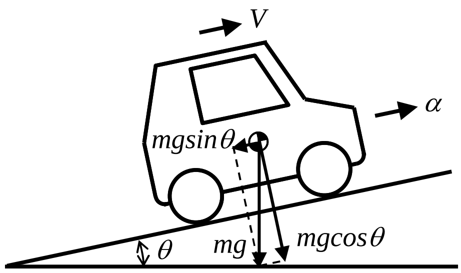


Figure 1: Components of force on a slope

stands for air density (kg/m^3), C_d stands for air resistance coefficient, A stands for frontal projected area (m^2), Δm stands for the equivalent mass of rotating parts (kg), and α stands for acceleration (m/s^2).

Based on the power output obtained from Formula (2.1) and the following equation, the required output of motor P_p (W) was calculated.

$$P_p = P/\eta_d \quad (P > 0) \qquad P_p = 0 \quad (P \le 0) \tag{2.2}$$

Here, η_d is mechanical efficiency of the vehicle.

Moreover, the energy consumption rate EC (km/kWh) and fuel consumption rate of the vehicle FC (km/L) were calculated based on the following formulas.

$$EC = \frac{D}{W_p/\eta_m - E_r} \times 3.6 \times 10^5 \tag{2.3}$$

$$FC = \frac{D}{W_p/(\eta_{th} \cdot d_{ge})} \tag{2.4}$$

where

$$W_p = \int_{t=0}^{T} P_p dt$$

$$E_r = \eta_r \cdot \int_{t=0}^{T} P dt$$

W_p stands for the total workload of a motor (J), E_r stands for the total regenerated energy (J), D stands for the total driving distance (km), η_m stands for the average motor efficiency, η_r stands for the average energy regeneration rate when reducing speed, η_{th} stands for the average thermal efficiency of the engine, and d_{ge} stands for the energy density of gasoline (J/L).

The following formula was used when calculating the amount of CO_2 emissions, CO_2 (g/km), as a greenhouse gas.

$$CO_2 = \frac{C_{co2\_e}}{EC} \times 1000 \quad or \quad \frac{C_{co2\_g}}{FC} \times 1000 \tag{2.5}$$

Where, C_{co2_e} stands for the CO_2 emission coefficient of electricity (kg/L) and C_{co2_g} stands for the CO_2 emission coefficient of gasoline (kg/kWh). The values C_{co2_e} = 0.332 kg/kWh and C_{co2_g} = 2.32 kg/L were used [1]. This value of CO_2 emission coefficient of electricity was estimated by Tokyo Electric Power Company for its operations in 2008. Its power supply composition ratio by energy source was as follows: 45% for LNG and LPG, 28% for nuclear energy, 12% for coal, 9% for petroleum, 5% for hydraulic energy, and 1% for others.

2.2 Calculation conditions

2.2.1 Driving mode

In this study, analyses were made assuming three different driving modes as shown in Table 1. Figure 2 displays the driving pattern under Condition I. The JC08 mode, which is Japan's test driving mode for determining fuel consumption and gas emission, was adopted for Condition I in order to simulate ordinary driving situations in Japan. However, it is highly possible that vehicle standards may be established based on the premise that UCVs will not be allowed to travel on highways due to practicality and safety considerations. On this account, the highway driving that occurs after the 1033 sec. point of the JC08 mode was excluded from the JC08 mode, and this was used as Condition I. Condition II dictates a smooth start of the vehicle on a slope, accelerating the vehicle at 2.7 km/h/s from the vehicle speed 0 to 30 km/h on a slope of 12% gradient which is the maximum allowed gradient for road design. For Condition III, created to test the requirement that there shall be no stalling on a steep slope, the vehicle is accelerated at 1.0 km/h/s from the vehicle speed 0 to 10 km/h on a slope of 30% gradient. The analyses of the amount of energy consumption and CO_2 emissions were conducted only under Condition I.

Table 1: Calculation driving mode

Condition	I	II	III
Driving mode	JC08 (w/o high way mode from 1033 sec)	V = 0-30 km/h α =2.7 km/h/s	V = 0-10 km/h α = 1.0 km/h/s
Road gradient [%]	0	12	30

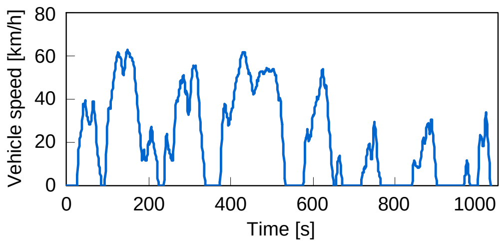


Figure 2: Driving pattern under Condition I

2.2.2 Assumed vehicle specifications

The specifications of the hypothetical vehicles that were the objects of the calculations are listed in Table 2. For the two-seater UCV, two types of the vehicle, Vehicle B and C, were hypothesized. A tandem type and a lateral type of seat arrangement were adopted for Vehicle B and Vehicle C, respectively. The tandem seat arrangement can reduce the air resistance because it allows for smaller width of the vehicle. Moreover, in order to make comparisons with these two-seater UCVs, analyses of vehicles equivalent to the mini-car and K-car in Japan were performed in the same way. Vehicle A was a single-seat ultra compact vehicle equivalent to a mini-car, Vehicle D was a two-seater vehicle equivalent to a K-car, and Vehicle E was a four-seater vehicle equivalent to a K-car. For each type of vehicle, calculations for both electric vehicles and gasoline-powered vehicles were performed. The vehicle weight was determined based on that of similar vehicles that are on the market. For the electric vehicles and gasoline-powered vehicles, the vehicle body weight, i.e. the weight of the vehicle after excluding the weight of the power train system (including batteries), was specified to be the same. Specifically, the determination of the vehicle weight was made by adding the weight of the power train system including the motor (assumed to be 5% of the body weight) and the battery weight for an electrical vehicle and the weight of the power train system including the engine (assumed to be 10% of the body weight) for a gasoline-powered vehicle to the vehicle body weight. Regarding the batteries, the specifications shown in Table 3 were assumed, and for each type of vehicle, the capacity was selected that allows driving distance of 100 km under Condition I with the maximum two persons seated in the vehicle. Hereinafter, a "-e" mark for an electrical vehicle and a "-g" mark for a gasoline-powered vehicle will be added when listed (for example, Vehicle A-e). In Table 4, the parameter

Table 2: Vehicle specifications for calculation

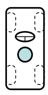
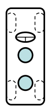
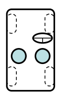
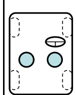
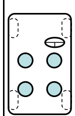
Vehicle	A	**B**	**C**	D	E
Type	Mini-car	**UCV**	**UCV**	K-car	K-car
Seat layout	Single 	**Tandem twin** 	**Lateral twin** 	Lateral twin 	Four 
Vehicle weight w/o P/T [kg]	285.0	**427.5**	**427.5**	501.7	712.5
Frontal projected area [m^2]	1.393	**1.393**	**1.820**	2.065	2.065

Table 3: Battery specifications for calculation

Battery type	Lithium-ion
Energy density per unit volume [kWh/L]	0.25
Energy density per unit mass [kWh/kg]	0.10
Power density per unit mass [kW/kg]	1.0

Table 4: Parameter values used in calculations

Vehicle type	Electric (-e)	Gasoline (-g)
P/T efficiency η_m, η_{th}	$\eta_m = 0.90$	$\eta_{th} = 0.20$
Recovery efficiency of braking energy η_r	0.45	0
D/T efficiency η_d	0.90	
Rolling resistance coefficient μ_r	0.0084	
Air resistance coefficient C_d	0.39	
Weight of passenger [kg/person]	55	

values used in the calculations are listed. For simplification, the values listed in Table 4 were assumed as constant for all vehicles.

3 Results and discussion

3.1 Calculation results of power requirement

Analysis was made to determine the maximum power output capacity that the motor needs when each of the above vehicles was driven under the Conditions I, II, and III with passengers in all the seats. As an example, the analysis results of the motor power needed for Vehicle C-e and E-e under Condition I are shown in Figure 3. The major differences between Vehicle C-e and E-e are the weight and frontal projection area. These differences changed the rolling resistance, air resistance, and acceleration resistance. Because of this, the driving power as well as power output that are defined in Formula (2.1) changed as well. This is the primary factor that generated a clear difference between the motor power needed for Vehicle C-e and for Vehicle E-e.

In Figure 3, the points of peak motor power output for both vehicles are shown. This result is defined to be the maximum power output for both vehicles under Condition I. The same analyses for other vehicles as well as other driving conditions were implemented, and the power requirements resulting from these calculations are shown in Figure 4. In this graph, since the Vehicle B and C UCVs had almost the same vehicle weight, their plots almost overlap.

Our results indicate that the power requirement changed in proportion to the gross vehicle weight for each condition. Moreover, Condition II required higher motor power than the other conditions in this study. Therefore, by satisfying

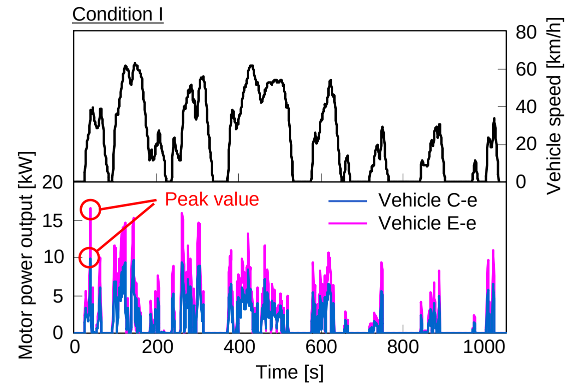


Figure 3: Calculation results of motor power output of vehicle C and E-e under Condition I

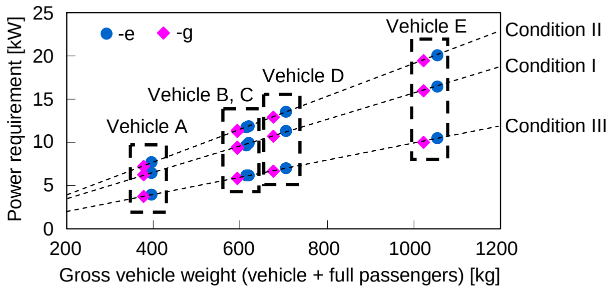


Figure 4: Calculated power requirements for each vehicle and condition

Condition II, it can be considered that driving is possible under the other conditions as well. The above results indicate that with the two-seater UCVs with the specifications assumed in this study, safe and smooth driving is made possible by mounting a motor that has a maximum output capacity of approximately 12 kW. This is close to that specified in the regulations for the L7 category of the World Forum for Harmonization of Vehicle Regulations (WP.29) of UN Economic Commission for Europe [2].

3.2 Estimation of engine displacement

We investigated how much engine displacement is needed if the motor in the vehicle above is an internal combustion engine (gasoline engine). Figure 5 shows the relationship between the displacement and the maximum power of the naturally aspirated gasoline engine of two-wheeled as well as four-wheeled vehicles in the Japanese market [3]. From this graph, it can be seen that the displacement and the maximum power of the naturally aspirated gasoline engine are roughly proportional. As a result, in order to achieve the motor output of approximately 12 kW necessary for the UCV investigated in the previous section in a gasoline engine, it can be seen that a displacement of approximately 200 – 250 cm^3 is sufficient.

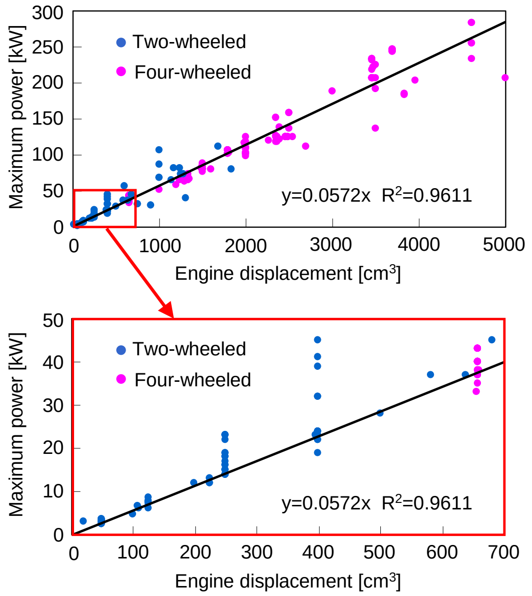


Figure 5: Relationship between displacement and maximum power of naturally aspirated gasoline engines in Japanese market

In this study, the engine maximum torque and the gear ratio of transmission were not taken into account. Therefore, the above result has possibility of small change when deciding engine displacement with considering these specifications.

3.3 Calculation results of energy consumption and CO_2 emission

In order to quantify the energy consumption and the CO_2 emission reduction effect of UCVs, the electricity or fuel consumption rate and the CO_2 emission of each type of vehicle were estimated based on analysis results. These estimates are shown in Figure 6. The calculations were made for vehicles driven under Condition I with two passengers (one passenger for Vehicle A). For Vehicle B and C, the two-seater UCVs, the electric consumption ratio or fuel consumption ratio was worse than Vehicle A due to the increased weight. However, it is indicated that improvement in the electric consumption ratio or fuel consumption ratio over Vehicle E can be expected, because of significant weight saving compared to Vehicle E. It also is shown that the CO_2 emission can be significantly reduced by electrifying the vehicle in addition to making the vehicle ultra compact. This is mainly because a power supply that emits less CO_2 is utilized, and because energy regeneration becomes possible when speed is reduced.

3.4 Discussion of total CO_2 reduction effect and initial and running cost of UCVs

The total CO_2 emission and total cost (vehicle + running cost) of Vehicle C-e, C-g, and E-g when their total mileages, i.e. their total driving distances, have reached various levels were calculated. For the calculations of Vehicle C-e, the specifications of the battery in 2010 and the battery in 2020 that were used were based on the technology roadmap drawn up by the New Energy and Industrial Technology Development Organization (NEDO) of Japan. These battery specifications are listed in Table 5 [4]. Moreover, costs of 18 yen/kWh for electricity and 120 yen/L for gasoline were assumed.

Figure 7 shows our estimates of the expenses of Vehicle C-e and Vehicle C-g in 2010 and in 2020, together with their CO_2 emission, when their total mileage has reached various levels, including both vehicle price and running cost. The vehicle price was estimated from the relationship between the vehicle weight and price of two-wheeled and four-wheeled vehicles in the Japanese market. After total mileage of 100000 km, with the Vehicle C-g we estimated a CO_2 emission reduction effect of approximately 2.5 tons compared to Vehicle E-g, and an effect of approximately 9 tons with Vehicle C-e.

Whether Vehicle C-e or Vehicle C-g is superior in terms of cost depends on the estimated price of the battery. Specifically, if the battery price drops down to the price estimated for 2020, Vehicle C-g is superior due to the extension of the driving

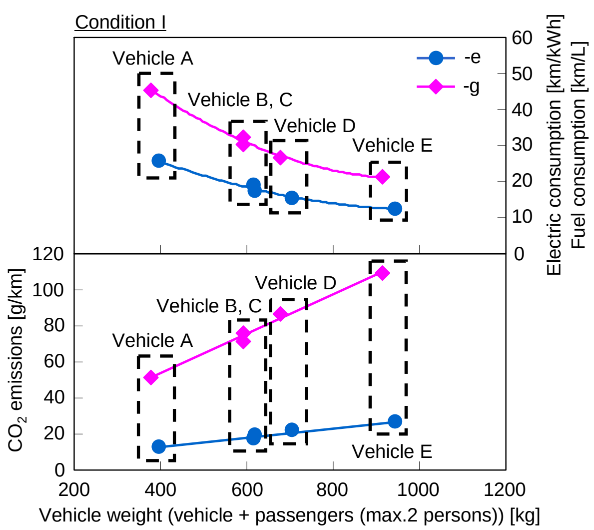


Figure 6: Calculated electricity or fuel consumption and CO_2 emission for each vehicle

Table 5: Battery specifications and price in the battery roadmap drawn up by NEDO

Year	2010	2020
Energy density per unit volume [kWh/L]	0.25	0.60
Energy density per unit mass [kWh/kg]	0.10	0.25
Power density per unit mass [kW/kg]	1.0	1.5
Price per unit energy [yen/kWh]	150,000	20,000

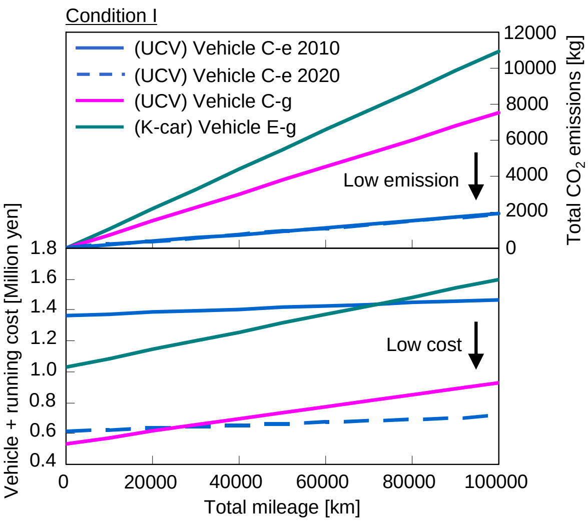


Figure 7: Estimated total CO_2 emission and total cost of vehicles with various mileages

distance. However, if the battery price does not change from 2010, there is no cost superiority over Vehicle C-g even after driving 100000 km. This can be considered as an important factor that would prevent the spread of ultra compact electric vehicles.

Therefore, price reduction of the battery is a very important requirement for the spread of these ultra compact electric vehicles.

The above estimates of CO_2 emission are largely dependent on our assumptions as to the thermal efficiency of the engine and the nature of the electric power supply. Therefore, it is necessary pay attention to trends in these items when calculating the CO_2 emission of each vehicle in the future.

4 Summary

For the establishment of a new vehicle standard for a two-seater UCV (ultra compact vehicle) in Japan, and determination of its motor power requirement, analysis and estimation of the energy consumption and CO_2 emission were conducted. Moreover, the total cost of driving different types of these vehicles was calculated. As a result, it has been confirmed that the regulations for the L7 category of the World Forum for Harmonization of Vehicle Regulations (WP.29) of the UN Economic Commission for Europe are satisfied, and that there should be no problem with driving these vehicles within Japan. In addition, for electric UCVs, it was shown that the reduction of the battery price is important in order to reduce the total cost to less than that of a UCV running on gasoline.

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