*Article*

# Change in Fuel Consumption of a Hybrid Vehicle When Operating in the Far North

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**Abstract:** This paper studies the effect of extremely low outdoor temperatures ($-40...-50\ °C$) on the increase in fuel consumption of a passenger car with a hybrid powertrain when operating in the far north regions. The experiment was carried out in the climatic conditions of the far north ern territory of the city of Yakutsk, Russia (Russian Federation). At the first stage of the experiment, data on fuel consumption of a hybrid vehicle in the summer season at an outdoor temperature in the range of $+20...+30\ °C$ were obtained. At the second stage of the experiment, data on fuel consumption of a hybrid vehicle in the winter season at extremely low outdoor temperatures in the range of $-40...-50\ °C$ were obtained. As a result, by comparing the fuel consumption data obtained in the first and second stages of the experiment, data on the effect of extremely low outdoor temperatures on fuel consumption of a hybrid vehicle were obtained. The obtained data may be of interest to manufacturers of hybrid vehicles, as well as to consumers of their products, including taxi services and individual car owners living (working) in the northern regions of the planet.

**Keywords:** hybrid car; fuel consumption; low outdoor temperatures

## 1. Introduction

Every year hybrid cars occupy an increasing share of the total number of passenger cars [1–3]. Models of vehicles with a hybrid system consisting of a gasoline engine, a battery and electric motors (Figure 1) are now offered by more than 70% [2–5] of car manufacturers. The main factor influencing the choice of a hybrid car by buyers is the economic effect of reducing fuel consumption compared to cars using a traditional system in the form of a gasoline or diesel engine.



**Figure 1.** Hybrid powertrain of a car (Source: https://hyperauto.ru/articles/poleznaya-informaciya/gibridy-na-moroze-osobennosti-zimney-ekspluatacii/, accessed on 27 June 2021).

The term electrified or hybrid powertrain is often used to describe several powertrain configurations that utilize electrical energy to produce propulsive torque [6,7]. Electrification within cars can take place in many different forms, including mild hybrid, strong hybrid, and plug-in hybrid [7–9]. Mild hybrid cars have the engine as the primary power source and use an electric motor with a small battery pack to produce electrical energy, which is used to assist with the engine output [7,10]. These cars usually do not have a dedicated driving mode that allows for propulsion via electrical power only, but the addition of electrification still helps reduce their fuel consumption in comparison to that of fossil-fuel-powered internal combustion engine cars. Strong hybrid cars, use a combination of an engine and a battery-powered electric motor to drive the car [7,11]. They have a more complex car architecture and physical packaging requirements than mild hybrid and conventional cars. Strong hybrid cars offer significant improvements in fuel consumption, as well as superior overall performance compared to similar conventional cars [7].

Considering the market of passenger cars with a hybrid powertrain in the regions of the far north of the Russian Federation, we see that it is represented by two types of such cars: the first type are new cars sold by dealerships of car manufacturers, and the second type are used cars supplied to market generally from Japan (97% of used hybrid vehicles supplied) [12].

Passenger cars with a hybrid powertrain sold in the regions of the far north of the Russian Federation are represented by the following models (Table 1).

**Table 1.** Main models of hybrid vehicles sold in the regions of the far north of the Russian Federation.

| Brand. | Model | Powertrain Type | Internal Combustion Engine Type (Included in the Powertrain of the Vehicle) | Internal Combustion Engine Capacity (cm$^3$) |
|---|---|---|---|---|
| Toyota | Prius | Hybrid | Gasoline | 1798 |
| | Toyota Harrier | Hybrid | Gasoline | 2500 |
| | Vellfire | Hybrid | Gasoline | 2500 |
| | Alphard | Hybrid | Gasoline | 2500 |
| | C-HR | Hybrid | Gasoline | 1800 |
| | Camry | Hybrid | Gasoline | 2500 |
| Honda | Vezel | Hybrid | Gasoline | 1500 |
| | Fit | Hybrid | Gasoline | 1500 |
| Nissan | Nissan Note | Hybrid | Gasoline | 1200 |
| | X-Trail | Hybrid | Gasoline | 2000 |
| Suzuki | Hustler | Hybrid | Gasoline | 700 |
| | Wagon R | Hybrid | Gasoline | 700 |

If we consider the commercial segment of the use of passenger cars with a hybrid powertrain, then these are, first of all, taxi services. So, the percentage of such cars now reaches 25–35% in taxi services in the regions of the far north of the Russian Federation. At the same time, in other regions of the country with a warm climate, the percentage of hybrid cars in taxi services already reaches 65–70%.

Approximately the same situation is observed in the segment of passenger cars used by private car owners. For example, in the Primorsky Territory (a region with a warm climate), the percentage of hybrid cars reaches 55%, while in the Republic of Sakha (Yakutia) (a region of the far north), the percentage of hybrid cars is 19%.

We conducted a survey in the Republic of Sakha (Yakutia) (Figure 2) among two respondent groups: 150 individual drivers and 150 taxi service drivers currently using cars with a traditional powertrain (diesel or gasoline engine). The respondents were asked what reasons are holding them back from purchasing a passenger car with a hybrid powertrain.
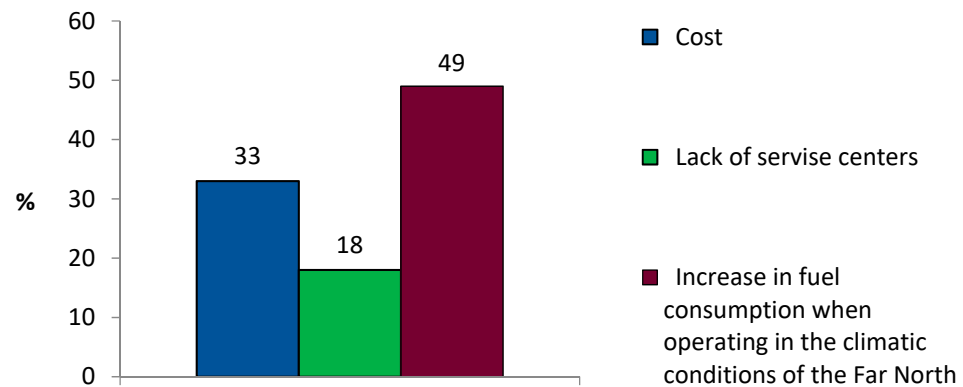
**Figure 2.** The results of a survey of drivers in the Republic of Sakha (Yakutia).

As a result of the survey, the following data were obtained (Figure 2).

Considering the results of the survey (Figure 2), we see that the primary reason that restrains drivers from purchasing passenger cars with a hybrid powertrain is the opinion of drivers that fuel consumption of a hybrid car will become more than declared by the manufacturer when it is used in the far north at constant low outdoor temperatures and will be comparable to fuel consumption of a car with a traditional powertrain (diesel or gasoline engine).

Considering that the cost of replacing the battery of a hybrid vehicle is on average 2000–4500 USD (depending on the car model), while the battery replacement is required on average every 240 thousand km of mileage (battery life in standard climatic conditions), the cost of operating a hybrid vehicle compared to the cost of operating a passenger car with a gasoline/diesel engine in the far north will become even higher. For this reason, 49% of drivers said that when buying their next car, they would prefer a car with a traditional (gasoline/diesel engine) rather than a hybrid powertrain.

We decided to analyze how reasonable the refusal of 49% of drivers living/working in the far north to buy a passenger car with a hybrid powertrain is, based on the opinion that fuel consumption of a hybrid car will increase when operating in the far north at low outdoor temperatures.

## 2. Literature Review

The development of methods for saving fuel by hybrid vehicles is the subject of the work of a number of authors [2–6,13–55].

Analyzing them, we can say that they studied various options for reducing fuel consumption of hybrid vehicles, including by regulating driving modes, changing the structure of the road surface, using different configurations of equipment, changing the structure of the battery et al., but at the same time it can be noted that the effect of extremely low outdoor temperatures on the change in fuel consumption of hybrid passenger cars has not been studied. The question of the dependence of fuel consumption of a hybrid vehicle on temperature conditions was considered in work [56]. The effect of the temperature of the hybrid vehicle battery on fuel consumption was considered in this paper. The authors found that changing the temperature of the battery to optimal values affects fuel economy up to 4.75%. In [39], the researchers also mentioned that battery temperature variations have a strong effect on both battery aging and battery performance. Significant temperature variations will lead to different battery behaviors. This influences the performance of the Hybrid Electric Vehicle (HEV) energy management strategies. In the context of this

study, these findings confirm that changing battery temperature, including cooling to low temperatures when interacting with low outdoor temperatures, can affect fuel consumption of a hybrid vehicle.

It is noted in papers [2,57,58], that cold weather and winter driving conditions can reduce your fuel economy significantly. Fuel economy tests show that, in city driving, a conventional gasoline car's gas mileage is roughly 15% lower at 20 °F than it would be at 77 °F. It can drop as much as 24% for short (3 to 4 mile) trips. The effect on hybrids is typically greater. Their fuel economy can drop about 30 to 34% under these conditions [2,57,58].

The authors of [22] recognized that although lithium-ion batteries have penetrated hybrid electric vehicles and pure electric vehicles (EVs), they suffer from significant power capability losses and reduced energy at low temperatures.

The authors noted that in order to evaluate those losses and to make an efficient design, good models are required for system simulation. Subzero battery operation involves nonclassical thermal behavior. Consequently, simple electrical models are not sufficient to predict bad performance or damage to systems involving batteries at subzero temperatures [22].

As can be observed based on the literature review and the above presented summary, there is a following research gap. Hybrid cars and their fuel consumption under different operating modes are quite often of interest to researchers, but at the same time, the effect of low outdoor temperatures has not yet been sufficiently considered. Only some references connected to analysis of the effect of low temperatures on fuel consumption for hybrid vehicles were found in acclaimed scientific databases (Scopus, Web of Science) in the analyzed period of time, namely [2,22,39,56–58]. There are currently no studies on the effect of extremely low temperatures (−40...−50 °C). It can be concluded that an experimental assessment of the impact of extremely low outdoor temperatures on fuel consumption of hybrid vehicles will largely fill this gap.

## 3. Experiment

To assess the effect of low outdoor temperatures on the change in fuel consumption of passenger cars with a hybrid powertrain, a field experiment method was chosen.

For the experiment, we used two Toyota Prius cars manufactured in 2019 and equipped with a hybrid powertrain (Figure 3).



**Figure 3.** Car model chosen for the experiment.

### 3.1. The Purpose of the Experiment

Obtain the result of the influence of low outdoor temperatures on fuel consumption of passenger cars with a hybrid powertrain.

### 3.2. The Object of the Experiment

A passenger car with a hybrid powertrain.

### 3.3. Location of the Experiment

For the experiment, the test site was chosen near the city of Yakutsk, Russia (Russian Federation) was selected (Figure 4).



**Figure 4.** Test site (Russian Federation, Yakutsk, Russia).

The length of the circular track is 1700 m. The road surface of the track is unpaved.

### 3.4. Technical Characteristics of Cars

For the experiment, two Toyota Prius cars with a hybrid powertrain were used (Table 2).

**Table 2.** Characteristics of cars.

| Cars | Mileage (T/km) | Hybrid Powertrain Elements | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | High Voltage Battery | | | Motor Generator | | Engine | |
| | | Type | Capacity (A h) | Maximum Power (kW) | Type | Maximum Voltage (V) | Type | Volume (cm$^3$) |
| num. 1 | 15 | nickel metal hydride | 6.5 | 37 | permanent magnet synchronous | 600 | gasoline | 1798 |
| num. 2 | 8 | nickel metal hydride | 6.5 | 37 | permanent magnet synchronous | 600 | gasoline | 1798 |

### 3.5. Procedure of the Experiment

The experiment was carried out in two stages.

In the first stage, the cars were moving in a circular horizontal track with fully charged batteries in conditions of positive outdoor temperatures (in the summer season). During the first stage of the experiment, each car traveled a distance of 300 km. The distance traveled by the car was recorded by the standard vehicle mileage counter. During the movement, the cars made only one stop to change the driver. In total, the first stage of the experiment took 7.3 h, while the stopping time for changing drivers was 5 min. When stopping to change drivers, the car engine was not turned off.

In the second phase, the cars were moving in a circular horizontal track with fully charged batteries in conditions of low outdoor temperatures (in the winter season). During the second stage of the experiment, each car traveled a distance of 300 km. The distance traveled by the car was recorded by the standard vehicle mileage counter. During the movement, the cars made only one stop to change the driver. In total, the second phase of

the experiment took 7.5 h, while the stopping time for changing drivers was 5 min. When stopping to change drivers, the car engine was not turned off.

In total, four drivers were involved in driving cars (two drivers for each car). The car drivers were the same in the two experiment stages.

## 4. Results and Discussion

### 4.1. Experiment Results

The first stage of the experiment was carried out on 20 July 2020. Actual modes of the experiment are presented in Table 3.

**Table 3.** Actual modes of the experiment.

| Mode | Value |
|---|---|
| travel speed, km/h | 40–50 |
| driving mode, urban/suburban/mixed | suburban |
| battery level (before the start of the 1st stage of the experiment), % | 73 (car num.1), 76 (car num.2) |
| battery level (at the end of the 1st stage of the experiment), % | 61 (car num.1), 75 (car num.2) |
| air temperature, °C | +23.....+25 |
| wind speed, m/s | 3–4 |
| gasoline, octane number | 95 |

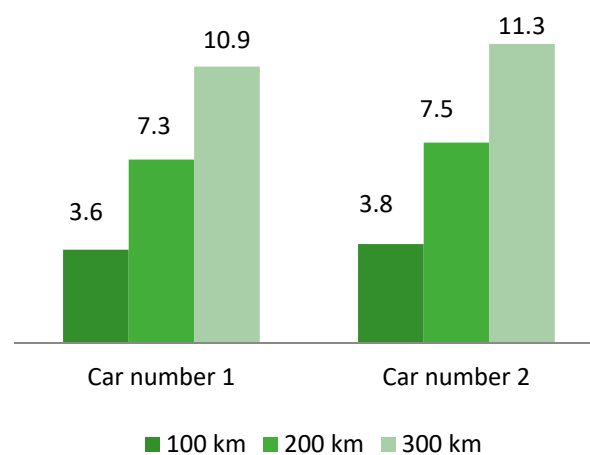The fuel consumption graph is shown in Figure 5.



**Figure 5.** Fuel consumption of cars.

The median fuel consumption L/100 km ($X$) during the first stage of the experiment was calculated using the formula:

$$X = \frac{X_1 + X_2}{2} / 3 = 3.7 \tag{1}$$

where $X_1$—fuel consumption of car no. 1 for travelling a distance of 300 km; $X_2$—fuel consumption of car no. 2 for travelling a distance of 300 km.

The second stage of the experiment was carried out on 15 January 2021.

Actual modes of the experiment are presented in Table 4.

**Table 4.** Actual modes of the experiment.

| Mode | Value |
| --- | --- |
| travel speed, km/h | 40–50 |
| driving mode, urban/suburban/mixed | suburban |
| battery level (before the start of the 2nd stage of the experiment), % | 77 (car num.1), 79 (car num.2) |
| battery level (at the end of the 2nd stage of the experiment), % | 63 (car num.1), 64 (car num.2) |
| air temperature, °C | −45.....−51 |
| wind speed, m/s | 7–11 |
| gasoline, octane number | 95 |

The fuel consumption graph is shown in Figure 6.
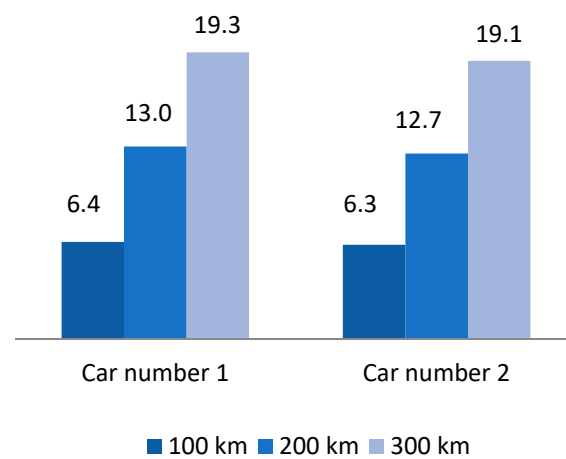
**Figure 6.** Fuel consumption of cars.

The median fuel consumption L/100 km ($Y$) is calculated using the formula:

$$Y = \frac{Y_1 + Y_2}{2}/3 = 6.4 \tag{2}$$

where $Y_1$—fuel consumption of car no. 1 for travelling a distance of 300 km; $Y_2$—fuel consumption of car no. 2 for travelling a distance of 300 km.

*4.2. Conclusions of the Experiment*

Comparing the obtained results of measurements of fuel consumption of a car with a hybrid powertrain when operating in warm outdoor temperatures (+20....+30 °C) and when operating in extremely low outdoor temperatures (−40....−50 °C), typical for the regions of the far north, we see that fuel consumption (95 octane gasoline) at an air temperature of −40...−50 °C will be 73% higher compared to fuel consumption at an air temperature of +20...+30 °C, and will be about 6–7 L per 100 km (when driving in suburban mode). The noted increase in fuel consumption is caused by the fact that at the second stage of the experiment, when hybrid cars were moving, their gasoline engine was almost not turned off, i.e., the car did not switch to the driving mode with electric motors. As a result, fuel consumption increased to the indicated values.

Comparing the obtained data on fuel consumption of a hybrid car, we see that the consumption of 6–7 L per 100 km will be comparable to fuel consumption of a car of the same class with a traditional powertrain (gasoline engine).

Therefore, it can be concluded that the reason for the refusal of drivers living in the far north to purchase a car with a hybrid powertrain, consisting in that fuel consumption

of a hybrid car when operating in the far north will be comparable to fuel consumption of a car with a traditional powertrain (diesel or gasoline engine), is justified.

## 5. Areas for Further Research

The experiment described in this study considered one model of hybrid cars, but it should be borne in mind that dozens of models of hybrid cars are known to be currently produced in the EU, USA, Japan, China, and a number of other countries. Fuel consumption figures for different models of hybrid vehicles can be different both in warm outdoor temperatures (+20....+30 °C) and when operating in extremely low outdoor temperatures (−40....−50 °C).

In this regard, it is of interest to conduct a series of similar experiments with models of hybrid vehicles of different manufacturers and different weights in order to obtain a more general picture of the effect of extremely low outdoor temperatures on the fuel consumption of hybrid vehicles.

## 6. Conclusions

During the study, data on the effect of extremely low outdoor temperatures on fuel consumption of a passenger car with a hybrid powertrain were obtained. The results of this study may be of interest to both private car owners and corporate car owners when deciding on the choice of the type of powertrain of the purchased cars. The results of the study allow concluding that car manufacturers should consider the option of special design modifications for passenger cars with a hybrid powertrain, which are sold in the regions of the far north, where low outdoor temperatures prevail for most of the year. It can be recommended to modify the battery case of the hybrid powertrain (its thermal insulation) in order to increase the battery resistance to extremely low outdoor temperatures. The solution of such a problem in accordance with the expressed opinion of drivers living/working in the regions of the far north can be of decisive importance when choosing between a car with a hybrid powertrain and a car with a gasoline (diesel) engine.

**Data Availability Statement:** No data were used to support this study.

**Conflicts of Interest:** The author declares no conflict of interest.

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