FUEL CELL VEHICLES VERSUS INTERNAL COMBUSTION ENGINE VEHICLES – THE PROFITABLENESS

Ion V. Ion, Ion C. Ioniţă

„Lower Danube" UNIVERSITY of Galaţi

***Rezumat.** Conştienţi că acum, în faza de început, competiţia dintre automobilul clasic, propulsat de motorul cu ardere internă şi vehiculul cu pilă de combustie (VPC) poate să trăiască şi să se dezvolte numai cu un suport financiar suplimentar, autorii şi-au concentrat atenţia asupra modelului matematic al acestui suport. Ei au identificat factorii de care depinde subvenţia şi condiţiile de rentabilitate pentru VPC. Studiul se bazează pe analiza comparată cost/calitate, dezvoltată în ultimii 10 ani.*

LIST OF THE USED SYMBOLS

Latin letters:

C_P^{ICE} – the total cost of a classical car, powered by internal combustion engine, [€ / ICE car]

C_P^{FCV} – the total cost of a FCV, [€ / FCV]

C_S^{ICE} – the cost of the transport service in the case ICE, [€/ km ICE]

C_S^{FCV} – the cost of the transport service with FCV, [€/ km FCV]

$\left(C_S^{ICE}\right)_I$ – the investment cost of the ICE transport service, [€ / km ICE]

$\left(C_S^{ICE}\right)_C$ – the consumption cost of the ICE transport service, [€ / km ICE]

$\left(C_S^{ICE}\right)_{OM}$ – the operation-maintenance cost of the ICE transport service, [€ / km ICE]

$\left(C_S^{FCV}\right)_I$ – the investment cost of the FCV transport service, [€ / km FCV]

$\left(C_S^{FCV}\right)_C$ – the consumption cost of the FCV transport service, [€ / km FCV]

$\left(C_S^{FCV}\right)_{OM}$ – the operation-maintenance cost of the FCV transport service, [€ / km FCV]

$\left(C_P^{ICE}\right)_I$ – the investment cost of the ICE car, [€/car ICE]

$\left(C_P^{ICE}\right)_C$ – the consumption cost of the ICE car, [€/car ICE]

$\left(C_P^{ICE}\right)_{OM}$ – the operation-maintenance cost of the ICE car, [€/car ICE]

$\left(C_P^{FCV}\right)_I$ – the investment cost of the FCV, [€/ FCV]

$\left(C_P^{FCV}\right)_C$ – the consumption cost of the FCV, [€ / FCV]

$\left(C_P^{FCV}\right)_{OM}$ – the operation-maintenance cost of the FCV, [€/ FCV]

s_{OM}^{FCV} – the operation-maintenance ratio of FCV car service, (eq. 8);

s_{OM}^{ICE} – the operation-maintenance ratio of ICE car service, (eq. 7);

f^{ICE} – the unitary fuel consumption of ICE, [l/100 km ICE];

c_f^{ICE} – the unitary cost for ICE fuel, [€ / l fuel ICE];

f^{FCV} – the unitary fuel consumption of FCV, [kg/100 km FCV];

c_f^{FCV} – the unitary cost for FCV fuel, [€ / kg fuel FCV];

p_{OM}^{ICE} – the operation-maintenance ratio of ICE car product, (eq. 11);

p_{OM}^{FCV} – the operation-maintenance ratio of FCV product, (eq. 12);

$S_{FCV}^{100\,km}$ – the state unitary subsidy of FCV program, [€/ 100 km];

Greek letters:

τ^{ICE} – the total life cycle of an ICE car, [km ICE / ICE car]

τ^{FCV} – the total life cycle of a FCV, [km FCV / FCV car]

Subscripts:

I – investment; *C* – consumption; *P* – product; *S* – service; *OM* – operation-maintenance; *f* – fuel; *FCV* – fuel cell vehicle

Superscripts:

ICE – internal combustion engine vehicle; *FCV* – fuel cell vehicle.

1. INTRODUCTION

The car's fuel cell system operates by electrochemically combining on-board hydrogen with oxygen taken from the air outside. Like batteries, fuel cells use electrodes (solid electrical conductors) in an electrolyte (an electrically conductive medium). When the hydrogen molecules come into contact with the negative electrodes, the molecules split into protons and electrons. The protons are carried across the proton exchange membrane to the positive electrode of the fuel cell, generating electricity. The molecules of the hydrogen and oxygen are combined chemically, with water as the "waste product." The only emission from the fuel cell will be water vapor.

The electricity generated from the fuel cells will be used by the car's electric induction motor/transaxle and electric power inverter to produce up to 90 kilowatts of power [20]. The electric power inverter works by converting the raw electrical current generated by the fuel cells into an alternating current that powers the electric motor and turns the wheels of the vehicle. A traditional car battery will be used to operate the car's electrical system, including the radio and air conditioning.

Hydrogen fuel-cell vehicles are seen as one possible way to dramatically cut the quantity of greenhouse gas emissions at some point in the future. The hydrogen used in the cells is extracted from natural gas, or petrol, and a simple chemical reaction between this and oxygen produces energy. However, producing the fuel itself would involve substantial carbon dioxide emissions, if it is produced from fossil energy and coupled with the extra "green" costs of fuel distribution, would cancel out these advantages. Professor John Heywood from MIT said: "If auto systems with significantly lower greenhouse gas emissions are required in say 30 to 50 years, hydrogen is the only major fuel option identified to date" [17].

The purpose of this paper is to analyze mathematically the conditions when FCV could be profitable. Starting on this way, we know that presently the classical cars are cheaper than FCV. This reality can be changed not so late in the future because of some tendencies we see:

1) the classical cars pollution is increasing permanently, due to raising number of vehicles, in spite of their lowering individual pollution;

2) the fuel cell technologies are permanently perfectible and their efficacy is continuously increasing while their cost is lower and lower;

3) the unitary cost of organic fuel is presently increasing exponentially. Being conscious that nowadays in the starting stage the competition between classical car, powered by combustion engine and the FCV can live and develop only with an additional financial support, the authors focused their attention on mathematical expression of this support. They found the factors affecting the value of this support and the conditions making FCV profitable.

The analysis is based on the compared cost-to-quality analysis, developed in the last 10 years [4–16]. To obtain the expression of the necessary subsidy, the authors considered two evident different cases:

a) the case of a classical car, powered by combustion engine (symbols with superscript ICE);

b) the case of a car powered by fuel cell system (symbols with superscript FCV).

2. CHOOSING THE NECESSARY COST-TO QUALITY RATIO

As the compared cost- to- quality analysis needs, when starting the evaluation it is necessary to choose an adequate cost-to quality ratio. There are two possible variants:

a. The production variant, where we have to calculate in terms of Euro/car;

b. The service variant, accountable in terms of Euro/100 covered kilometers.

The authors considered the second variant option (b) to be more appropriate because it expresses better the service the car does, taking into consideration that the car is used more or less during its life cycle span.

3. THE QUALITY PARAMETERS OF THE CONSIDERED CARS

For each car, classical or hybrid one, there are 31 different quality parameters: QP 01–Accessibility; QP 02–Adaptability; QP 03–Availability; QP 04–Cleanliness; QP 05–Credibility; QP 06–Durability; QP 07–Environmental Protection; QP 08–Fuel Consumption; QP 09–Functional Engine Parameters; QP 10–Inflammability; QP 11–Lighting Parameters; QP 12–Look; QP 13–Maintainability; QP 14–Parking Capacity; QP 15–Productivity; QP 16–Promptitude; QP 17–Protection; QP 18-PV Fuel Cell Parameters; QP 19-Reliability; QP 20–Safety; QP 21–Size; QP 22–Style; QP 23–Susceptibility; QP 24–Pneumatic Tires Parameters; QP 25–Toxicity; QP 26–Transportability; QP 27–Transport Capacity; QP 28–Vulnerability; QP 29–Watching capacity; QP 30–Weight; QP 31–Workings.

When considering the transport service made by these cars, we have at least another 15 parameters: QS 01–Accessibility; QS 02–Accuracy; QS 03–Comfort; QS 04–Competence; QS 05–Confidence; QS 06–Credibility; QS 07–Efficacy; QS 08–Efficiency; QS 09–Feedback speed; QS 10–Formalism; QS 11–Honesty; QS 12–Proficiency; QS 13–Promptitude; QS 14–Punctuality; QS 15–Safety.

4. THE COST EQUATION

The total cost of the purchased ICE car is:

$$C_P^{ICE} = \left(C_P^{ICE}\right)_I + \left(C_P^{ICE}\right)_C + \left(C_P^{ICE}\right)_{OM} \quad [€/\text{ICE car}] \qquad (1)$$

The total cost of the purchased FCV is:

$$C_P^{FCV} = \left(C_P^{FCV}\right)_I + \left(C_P^{FCV}\right)_C + \left(C_P^{FCV}\right)_{OM} \quad [€/\text{FCV car}] \qquad (2)$$

The total cost of the ICE car transport service is:

$$C_S^{ICE} = \left(C_S^{ICE}\right)_I + \left(C_S^{ICE}\right)_C + \left(C_S^{ICE}\right)_{OM} \quad [€/\text{km ICE}] \qquad (3)$$

The total cost of the FCV transport service is:

$$C_S^{FCV} = \left(C_S^{FCV}\right)_I + \left(C_S^{FCV}\right)_C + \left(C_S^{FCV}\right)_{OM} \quad [€/\text{km FCV}] \qquad (4)$$

Taking into consideration that:

$$\left(C_S^{ICE}\right)_I = C_P^{ICE} / \tau^{ICE} \quad [€/\text{km ICE}] \qquad (5)$$

$$\left(C_S^{FCV}\right)_I = C_P^{FCV} / \tau^{FCV} \quad [€/\text{km FCV}] \qquad (6)$$

$$\left(C_S^{ICE}\right)_{OM} = s_{OM}^{ICE} (C_S^{ICE})_I \quad [€/\text{km ICE}] \qquad (7)$$

$$\left(C_S^{FCV}\right)_{OM} = s_{OM}^{FCV} (C_S^{FCV})_I \quad [€/\text{km FCV}] \qquad (8)$$

$$\left(C_S^{ICE}\right)_C = f^{ICE} c_f^{ICE} \quad [€/\text{ km ICE}] \qquad (9)$$

$$\left(C_S^{FCV}\right)_C = f^{FCV} c_f^{FCV} \quad [€/\text{ km FCV}] \qquad (10)$$

$$\left(C_P^{ICE}\right)_{OM} = p_{OM}^{ICE} \quad (C_P^{ICE})_I \quad [€ / \text{ICE car}] \qquad (11)$$

$$\left(C_P^{FCV}\right)_{OM} = p_{OM}^{FCV} \quad (C_P^{FCV})_I \ [€ / \mathrm{FCV}] \tag{12}$$

the expression of ICE transport cost becomes:

$$C_S^{ICE} = \left(1+s_{OM}^{ICE}\right)[(1+p_{OM}^{ICE})\,(C_P^{ICE})_I + \left(C_P^{ICE}\right)_C]/\tau^{ICE} + f^{ICE}\,c_f^{ICE} \quad [€/\mathrm{km\ ICE}] \tag{13}$$

while that of FCV transport cost is:

$$C_S^{FCV} = \left(1+s_{OM}^{FCV}\right)[(1+p_{OM}^{FCV})(C_P^{FCV})_I + \left(C_P^{FCV}\right)_C]/\tau^{FCV} + \\ + f^{FCV}\,c_f^{FCV} \quad [€/\mathrm{km\ FCV}] \tag{14}$$

5. THE STATE SUBSIDY

Knowing that presently the ICE transport is cheaper than that of FCV:

$$C_S^{ICE} < C_S^{FCV} \quad [€ / \mathrm{km}] \tag{15}$$

to encourage the development of FCV research and development it is necessary the subsidy S_{FCV}^{km}, so that:

$$C_S^{ICE} + S_{FCV}^{km} = C_S^{FCV} \ [€ / \mathrm{km}] \tag{16}$$

From equations (13), (14) and (16) we can obtain the expression of the necessary subsidy:

$$S_{FCV}^{km} = \left(1+s_{OM}^{FCV}\right)\left[\left(1+p_{OM}^{FCV}\right)\left(C_p^{FCV}\right)_I + \left(C_p^{FCV}\right)_c\right]/\tau^{FCV} - \\ -\left(1+s_{OM}^{ICE}\right)\left[\left(1+p_{OM}^{ICE}\right)\left(C_p^{ICE}\right)_I + \left(C_p^{ICE}{}_c\right)\right]/\tau^{ICE} + \\ + f^{FCV}c_f^{FCV} - f^{ICE}c_f^{ICE} \qquad [€ / \mathrm{km}] \tag{17}$$

6. THE PROFITABLENESS OF FCV

The equation (17) is essential when analyzing the profitableness of FCV. It allows us to see the influence of the main factors, to find out how could we give up to subsidy S_{HSV}^{km}, making the FCV profitable. For this, we have to consider

$$S_{FCV}^{km} = 0 \tag{18}$$

In this case

$$\left(1+s_{OM}^{FCV}\right)\left[\left(1+p_{OM}^{FCV}\right)\left(C_p^{FCV}\right)_I + \left(C_p^{FCV}\right)_c\right]/\tau^{FCV} = \\ = \left(1+s_{OM}^{ICE}\right)\left[\left(1+p_{OM}^{ICE}\right)\left(C_p^{ICE}\right)_I + \left(C_p^{ICE}\right)_c\right]/\tau^{ICE} + \\ + f^{FCV}c_f^{FCV} - f^{ICE}c_f^{ICE} \quad [€ / \mathrm{km}] \tag{19}$$

7. MATHEMATICAL MODELING, RESULTS AND DISCUSSION

In the reference papers [17, 20] we found reasons to consider $C_p^{FCV} = 2C_p^{ICE}$; $\left(C_p^{FCV}\right)_{OM} = \left(C_p^{ICE}\right)_{OM}$; $\tau^{ICE} = 0.5\,\tau^{FCV}$; $c_f^{ICE} = 1.77...3.54$ €/l fuel ICE; $c_f^{FCV} = 6.25...4.38$ €/kg fuel FCV; $f^{FCV} = 1.7$ kg/100 km FCV; $\tau^{FCV} = 10$ years = 150 000 km FCV.

These data are argued below. From [17, 18, 19] we can read:

- Fuel cell vehicles will be affordable by the time they reach the marketplace.
- Hydrogen opponents look at the price of today's hand-built prototypes and today's stationary power generation systems and leap to the conclusion that fuel cell vehicles will not be cost-competitive. They ignore that prototypes and first-generation systems are almost always very expensive compared with mass produced units. Just like gasoline powered cars, personal computers, digital cameras, and many other innovative products, the price will come down.
- Costs have come down dramatically. The USA Department of Energy, based on current best technology, projects cost of a fuel cell vehicle engine at \$225 per kilowatt in mass production. Industry's ultimate goal is \$30 to \$50. The best of today's research vehicles report range of well more than 322 km using conventional compressed hydrogen storage. Ford designed a fuel cell vehicle with range of 612 km using pressurized tanks (345 bars). Several vehicles are operating on non-gaseous alternatives that achieve fully commercial range. (more than 483 km).
- Hydrogen is as safe if not safer than conventional fuels on the market today. Hydrogen is different than gasoline and other fuels, so safety procedures will need to be revised. A Norwegian study in 2002 reached a similar conclusion: "There are no technical or safety barriers that prevent the use of hydrogen for fuel in the transportation sector or as a medium for the storage and transportation of energy. It is possible to manufacture and utilize hydrogen just as safely as with today's gasoline systems"[17].
- The USA National Academy of Sciences/National Research Council studied this question. Data provided in the NRC report show that the cost of hydrogen *per mile driven* ought to be between 27% to 52% lower than the cost of gasoline at \$1.80/gallon in a conventional car, and between 3% more to 32% less than the cost of gasoline used in a hybrid electric vehicle. Even if hydrogen ultimately is more expensive by weight or volume, hydrogen cars are much more efficient than gasoline cars, thus making hydrogen very competitive on a cost per mile basis. Fuel cell vehicles are 50 percent efficient, compared to perhaps 15 percent for gasoline combustion engines. On this basis, the per-mile costs for fuel cell vehicles are comparable to gasoline vehicles even with today's prototypes. Gasoline prices are rising rapidly and show no signs of abating. Gasoline is nearing \$3 per gallon today in some areas, and is well above \$2 in others. Consumers will be able to buy hydrogen at energy stations. Some may even choose to generate hydrogen at home using small systems called electrolyzers that make hydrogen from water using electricity.
- Only hydrogen offers the promise of completely removing motor vehicles from the pollution equation.

A comparison between ICE and FCV regarding the fuel economy and pollutant emissions is shown in table 1.

Table 1. Fuel economy in 2015 and carbon emission

	ICE	FCV	
		actual	optimistic
Fuel economy in 2015	9.801 l/100 km	405 l/100 km	
Carbon emission (grams of carbon/km)	81.25	35.63	30.62

A gasoline engine can produce one kilowatt of energy for about $50, while a one-kilowatt fuel cell on the market today costs around $5,000. A car hydrogen storage unit can carry about 18 pounds of hydrogen, equivalent in power to 16 gallons of gas. That gives it a range of about 300 miles--on the low end compared with conventional cars. A hydrogen fill-up costs about $40, making it about 16% cheaper than $3 a gallon gas.

Reading this large variety of documentary reasons, the reader can understand better how difficult was the authors' task to collect numerical data for their study. Finally the authors made the following hypotheses:

$$s_{OM}^{FCV} = 0.07\,;\; s_{OM}^{ICE} = 0.05\,;\; C_p^{ICE} = 10000\text{ €};$$

$$p_{OM}^{FCV} = 0.10\,;\; p_{OM}^{ICE} = 0.40\,;\; \tau^{ICE} = 75000\text{ km ICE};$$

$$\left(C_p^{FCV}\right)_C = 1.2\,\left(C_p^{ICE}\right)_C\,;\; f^{ICE} = 7\text{ l/100 km ICE};$$

$$\left(C_p^{ICE}\right)_I = 0.4\,C_p^{ICE}\,;\; \left(C_p^{ICE}\right)_C = 0.4\,C_p^{ICE}\,.$$

By using these data and the mathematical model previously presented, the functions $S_{FCV}^{100\,km}(\tau^{FCV})$ (fig. 1) and $S_{FCV}^{100\,km}(c_f^{ICE})$ (fig. 2) were calculated.

Table 2. Assumed lifetime and operations and maintenance cost, and estimated specific costs for the hydrogen energy system components at present and in 2020 [20]

Hydrogen technology component	Type	2003			Long-term (2020)		
		Lifetime (years)	O&M (% of inv.costs)	Cost	Lifetime (years)	O&M (% of inv.costs)	Cost
Electrolyser	Alkaline (30bar outlet pressure)	20	2.0	8,150 €/Nm³/h	20	1.0	4.075 €/Nm³/h
Fuel Cell	PEM-type	10	2.5	3,000 €/Nm³/h	20	1.0	300 €/kW
H₂-storage unit	Compressed gas (30 bar)	20	0.5	38 €/Nm³	20	0.5	25 €/Nm³

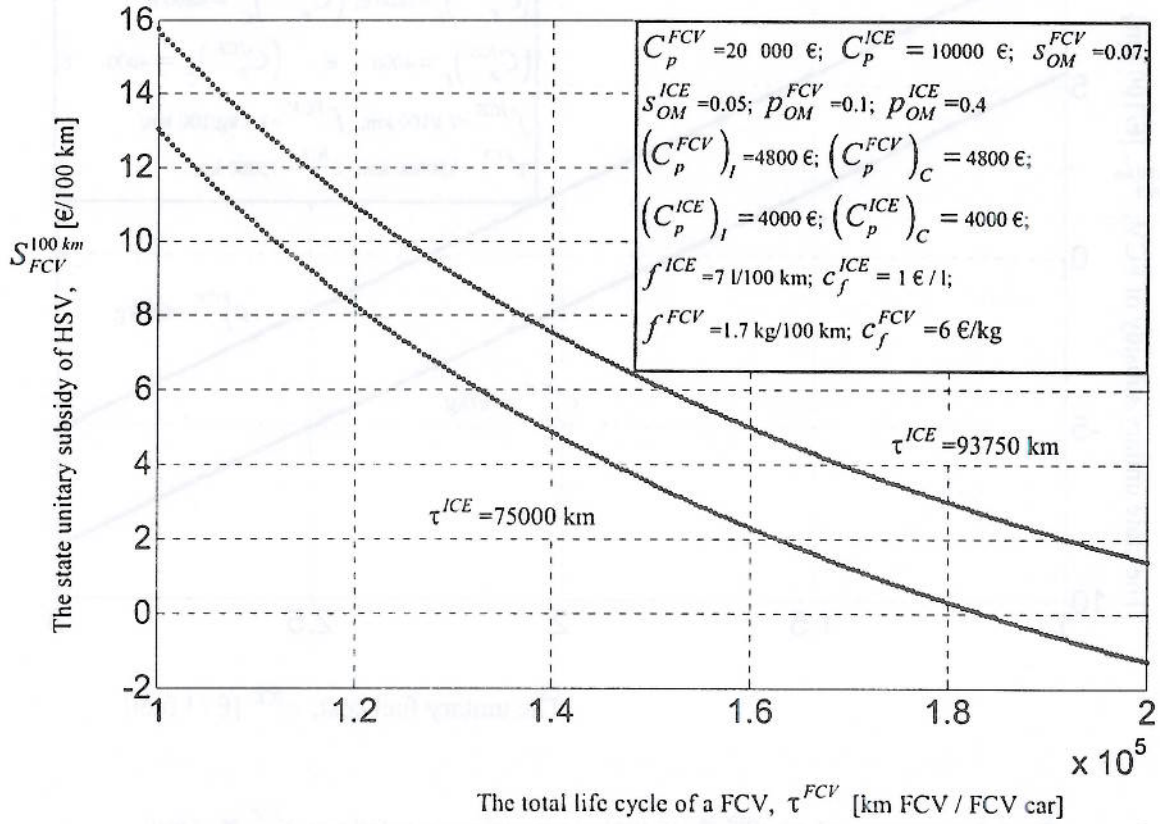

Fig. 1. The necessary subsidy $S_{FCV}^{100\,km}$ [€/100km] versus the total life cycle of FCV τ^{FCV} [km FCV / FCV car].

From the fig. 1 we can see how the state unitary subsidy of FCV $S_{FCV}^{100\,km}$ [€ / 100 km] is influenced by total life cycle of a FCV, τ^{FCV} [km FCV/ FCV car]. The diagram was calculated with the values previously indicated and inserted in diagram field. The compared cost-to-quality analysis applied here shows us that:

1. The state unitary subsidy $S_{FCV}^{100\,km}$ [€ / 100 km] is lowering when the total life cycle of FCV τ^{FCV} [km FCV/ FCV car] is increasing. In other words, the more resistant in time is FCV, the less is the necessary unitary state subsidy. How much must be this total life cycle of FCV so that the state subsidy to not be necessary? The calculus results shows τ^{FCV} = 830000 km for τ^{ICE} = 75000 km and τ^{FCV} =101500 km when τ^{ICE} = 93750 km. Of course, these results are unacceptable, we must have in view other practical solutions, like to manufacture cheaper the FCV (the value C_P^{FCV}).
2. The fig. 1 diagram shows also that the less is the total life cycle of the ICE cars (the value τ^{ICE}) the unitary state subsidy $S_{FCV}^{100\,km}$ [€ / 100 km] is lower.

Fig. 2 is showing intuitional conclusions:

1) The necessary subsidy $S_{FCV}^{100\,km}$, [€/100 km] decreases when the unitary fuel cost c_f^{ICE} [€ / l fuel] increases.
2) The necessary subsidy $S_{FCV}^{100\,km}$, [€/100 km] decreases when the unitary cost for FCV fuel c_f^{FCV} [€ / kg fuel FCV] decreases too.

8. FINAL CONCLUSION

According to the done study there is a real feasible solution to make FCV profitable in the next future. This solution is characterized by the following numerical parameters:

1. The total cost of FCV C_P^{FCV}=13000 €;
2. The total cost of classical car, powered by internal combustion engine, C_P^{ICE} = 10000 €;
3. The operation-maintenance ratio of ICE car service (eq. 7), $s_{OM}^{ICE} = 0.05$;
4. The operation-maintenance ratio of ICE car product, p_{OM}^{ICE} (eq. 11) and p_{OM}^{FCV} -the operation-maintenance ratio of FCV product, (eq. 12) $p_{OM}^{FCV} = p_{OM}^{ICE} = 0.40$;

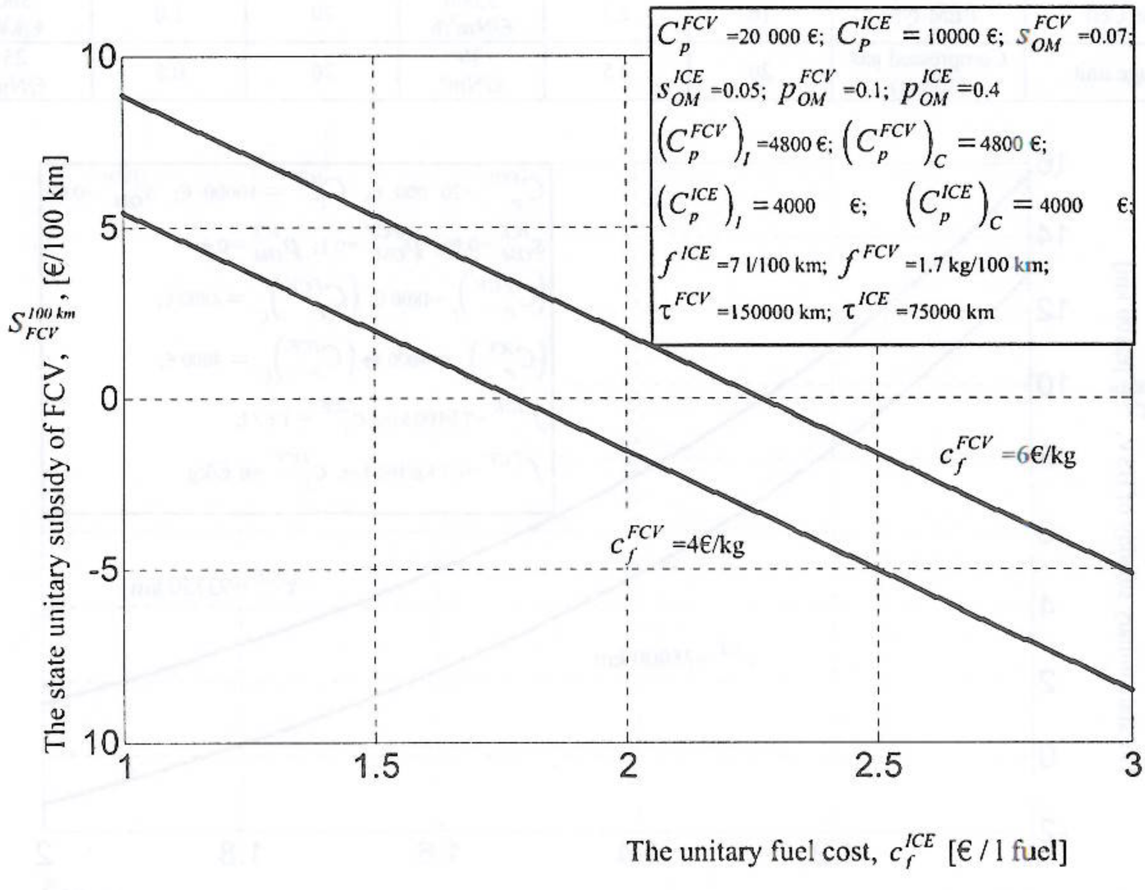

Fig. 2. The necessary subsidy $S_{FCV}^{100\,km}$, [€/100 km] versus the unitary fuel cost c_f^{ICE} [€ / l fuel].

5. The investment cost of the FCV, $\left(C_p^{FCV}\right)_I = 4800$ €;
6. The operation-maintenance ratio of FCV car service (eq. 8), $s_{OM}^{FCV} = 0.07$;
7. The consumption cost of the FCV, $\left(C_p^{FCV}\right)_C = 4800$ €;
8. The investment cost of the ICE car, $\left(C_p^{ICE}\right)_I = 4000$ €;
9. The consumption cost of the ICE car, $\left(C_p^{ICE}\right)_C = 4000$ €;
10. The unitary fuel consumption of ICE, $f^{ICE} = 7$ l / 100 km;
11. The total life cycle of an ICE car, τ^{ICE} [km ICE / ICE car] and τ^{FCV} -the total life cycle of a FCV, [km FCV / FCV car] $\tau^{ICE} = \tau^{FCV} = 75000$ km.

Of course, this is only one of the possible solutions. The done mathematical model presented here allows the modeling according to concrete possibilities the manufacturer has in order to achieve a better and better FCV. Modeling so, using the compared cost-to-quality analysis as work procedure, the authors are convinced that the best solution of a FCV is an ideal [12, 16, 17, 18], untouchable as any ideal, but an aim point for researchers.

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