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Analysis of Vehicle Dynamics Parameters for Electric Go-Kart (eKart) Design

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Today electric vehicles are becoming increasingly popular in our lives. In motorsport, however, they are not as widely used. Formula E, which was created to boost electric motorsport, is not enough to popularize it. Every driver wanting to advance to F1 (highest rank racing series) has to start from karting between the ages of 5 and 8. But today go-karts are only powered by combustion engines.
In order to provide young drivers with the possibility of racing small electric vehicles, the so called eKarts, combustion engines have to be replaced with electric motors. EKarts should offer similar performance to combustion engine go-karts. Therefore to determine the required power of the electric motors and the capacity of the batteries in eKarts for different age categories, the technical parameters of the different age categories of combustion engine racing go-karts were analyzed in this paper.
In this paper it was proved that present Li-Ion battery technology makes it possible to construct eKarts for children's and junior categories. With the current technology, it is not possible to create an eKart for senior categories (15 and over) in line with the current regulations for go-karts.

Keywords: eKart, electric motorsport, formula-e, go-karts.

1. Introduction

The history of the electric car started at the beginning of the automobile era, i.e. in the 19th century. At that time, electric vehicles competed with combustion and steam engine ones not only in the streets but also on race tracks. The world land speed record of 105.88 km/h was established by the Belgian Camille Jenats in 1899 in an electric vehicle and was unbeaten for another 3 years [1] [2]. The Paris-Bordeaux-Paris race was attended by the French electric constructor Charles Jeantud. His car offered great performance, but its 950-kg batteries had to be replaced 15 times during the race [3]. The problem with storing electricity was the reason why electric vehicles have long disappeared from the streets and from motorsport as well.

Rising awareness of ecology and the search for new fields of experiments in motorsport have led to the development of hybrid technology, which was the first sign of a return to electricity. In the F1 racing series, fuel efficiency regulations have been intensified and the share of hybrid energy recovery systems has increased. In 2006 regulations were announced and in 2009 a kinetic energy recovery system was introduced in the F1 racing series. The system called KERS (Kinetic Energy Recovery System) allowed the release of energy up to 400 kJ on one lap [6,8] and no more than 60 kW. In long-distance races the importance of the hybrid system has been confirmed in the most prestigious race. In the LeMans race on 16-17 June 2012 two Audi hybrid cars were classified in the first two places. This was the first long-distance race for hybrid vehicles, as apart from the Audi LMP1 e-tron, Toyota also entered its TS030 hybrid vehicle.

Another step towards ecological motorsport was the creation of the electric Formula E series. In Formula E the race takes about 50 minutes, and the problem of storing a sufficient amount of energy has been resolved by the obligatory pit-stop and car replacement. Formula E takes advantage of easy energy control and makes the sport more entertaining. In racing mode maximum power is limited to 170 kW. However, the three drivers who win a fan on-line vote can receive an additional 100 kJ increasing maximum power to 200 kW for couple of seconds.

Formula E has received credit from racing drivers. Former F1 driver and current Formula E driver, Nelson Piquet Jr, said that "if you care about the fame and flashes the F1 is the best racing series, but equally exciting for racing drivers is competing in Formula E. Formula E was created to boost electric motorsport, but still very few series are purely electric.

To get to F1 each driver has to start from karting between the ages of 5 and 8. But present-day go-karts are only powered by combustion engines. In order to introduce for young drivers the possibility of racing small electric racing vehicles, the so called eKarts, combustion engines have to be replaced with electric motors. It was assumed that for eKarts to gain a foothold, they should provide similar parameters to those of combustion engine go-karts. Therefore to determine the required power of the electric motors and the capacity of the batteries in eKarts for different age categories, the technical parameters of the different age categories of combustion engine racing go-karts have been analyzed.

The Rotax Max Challenge series has been chosen for analysis due to the fact that it is one of the most popular karting series in the world, and also in Poland. Table 1 shows the main features of selected Rotax categories.

An analysis of the power used by go-karts was made on the basis of data from racing and official trainings on the following certified karting tracks:

Speedworld in Bruck, Austria – length 1060 m, 1120 m, 1140 m (depending on configuration), 8-10 m wide, clockwise direction.

Goethe Stadium in Keckemet, Hungary – length 935 m, 7 m wide, anti-clockwise.

Pann Ring in Ostffyasszonyfa, Hungary – length 1071 m, 8 m wide counterclockwise direction.

Autodromo Vysoke Myto in Vysoke Myto, Czech Republic – length 1142 m, 8 m

Table 1 Main parameters of the Rotax series in Poland

	MicroMax	MiniMax	JuniorMax	SeniorMax	DD2
Driver age [years]	8-10	10-13	13-16	15+	15+
Min. mass of vehicle with driver [kg]	110	130	147	165	173
Chassis type, wheelbase [mm]	950	1050	1050	1050	1050
Power max. [kW/rpm].	6/7500	11/8500	17/8500	22/8500	25/8500
Torque [Nm/rpm]	9/6000	13/8000	19/8500	21/9000	22/10500
Mass of drive train [kg]	21,6	23,0	23,0	23,1	28,8
Mass of fuel [kg]	∼4,0	∼5,0	∼6,0	∼7,0	∼7,0
Race distance [km]	14	16	18	20	20

clockwise directional width, Figure 4.4 Photo of Autodromo Vysoke Myto.

Tor Radom, in Radom, Poland - length 820 m, 8-12 m in clockwise direction (possibly also in the opposite direction).

Bydgoszcz in the city of Bydgoszcz, Poland – length 1017 m, 8-10 m wide counterclockwise direction.

7 Laghi Kart - International Circuit in Castelletto di Branduzzo, Italy - length 1017 m, 8-10 m in clockwise direction.

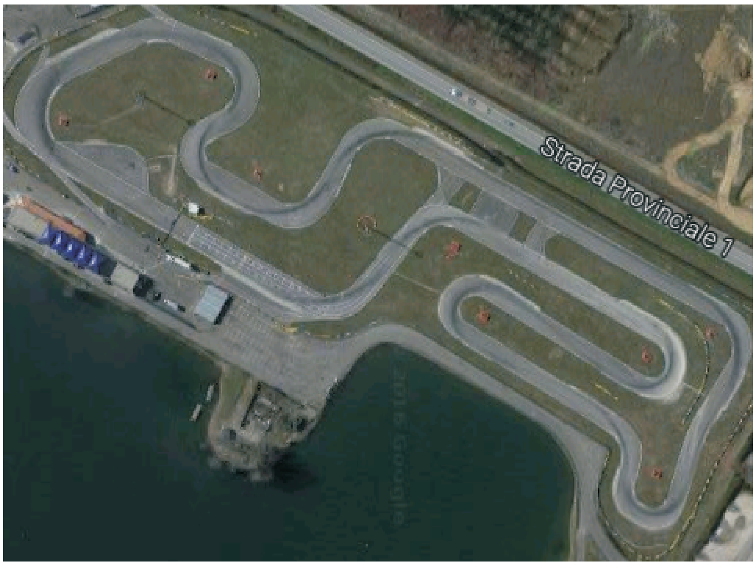

Figure 1 Picture of 7 Laghi Kart - International Circuit © Google Maps

In each of the age categories data from a dozen race laps was analyzed and for each six races were selected, three fastest and three slowest lap times for three different racetracks. An Off Camber Data tool for Unipro devices was used for the analysis. Fig. 2 shows the Off Camber Data analysis panel.

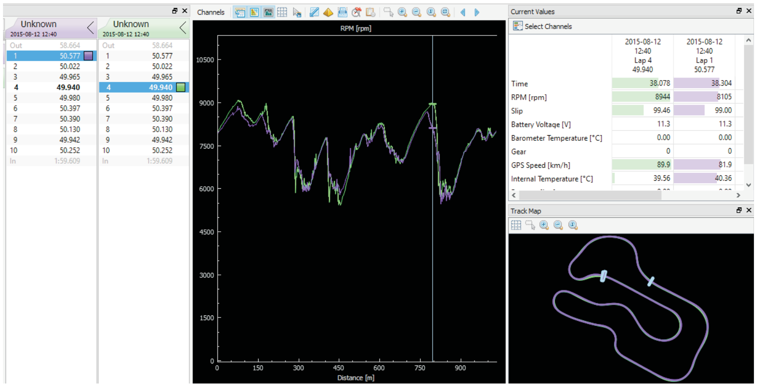

Figure 2 Analytical panel Off Camber Data application

2. Model of go-kart energy usage

In order to determine energy requirements, the model assumes that the energy stored in batteries E_B must provide the possibility to finish a maximum duration race (based on the Rotax Max Challenge 2016 Cup) with the go-kart using maximum power, which was experimentally derived on different racetracks in Poland and Europe:

$$E_B = W_{Rmax}\, n \tag{1}$$

where:
E_B – energy stored in batteries [kWh],
W_{Rmax} – work done by running go-kart during the race with maximum energy consumption [kWh],
n – coefficient of securing sufficient level of energy [%].

In simplified terms it was assumed that W_{Rmax} is the work done by the combustion engine of a go-kart of average power P_{Omax} throughout the maximum duration of the race t_{Rmax}:

$$W_{Rmax} = P_{Omax}\, t_{Rmax} \tag{2}$$

where:
t_{Rmax} – the maximum duration of the race based on an analysis of the Rotax Max Challenge 2016 Polish Championships [s],
P_{Omax}– average power used by go-kart during a lap with the highest power usage [kW].

P_{Omax} was obtained by selecting the highest value from the calculated average power P_Os, for six different cases of go-kart racing in a given age category. We chose the shortest and longest run times on three racetracks with different characteristics.

The model assumes that the energy used on one lap P_O is equal to the sum of instantaneous power calculations in tenths of a second of the lap.

$$P_O = \frac{\sum_{i=0}^{N_O} P_{ch}}{N_O} \tag{3}$$

where:
P_O – average power value used during lap [kW],
P_{ch} – instantaneous power [kW],
N_O – number of measurements (measurement in 0.1s intervals).

In the presented approach it was assumed that P_{ch} – instantaneous power is calculated based on instantaneous engine rpm and the engine power/rpm specification curve presented in Fig 4. Due to permanent coupling of the engine with the drive axle, in the course of the analysis braking periods during the lap were identified and excluded from the calculation of average power. Based on observations and analysis, it was assumed that braking is a decrease in engine speed of at least 300 rpm with at least three measuring periods i.e. over 0.3 seconds and is associated with a significant decrease in vehicle speed i.e. at least 2 km in 0.1s.

2.1. *Analysis of race durations in the Rotax Max Challenge Poland Championships in 2016*

Following equation (2), it was necessary to analyze the duration of races t_{Rmax} to calculate the work performed by the power train. This analysis is based on the duration of go-kart races in the 12 rounds of the Rotax Max Challenge Poland Championships in 2016.

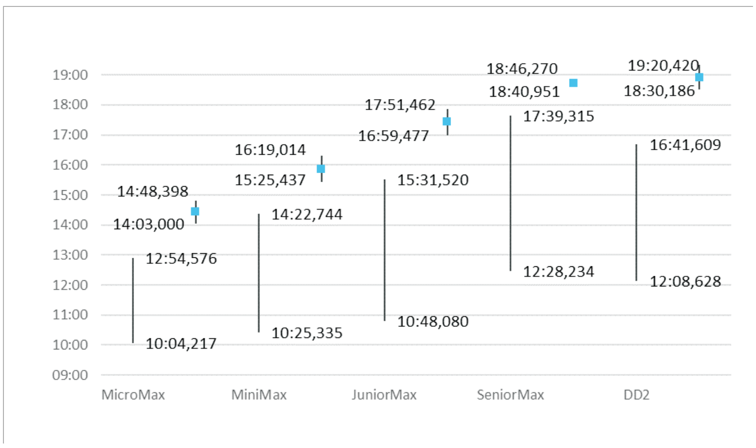

Figure 3 Race durations in Rotax Max Challenge Poland Championships 2016 for given categories

The analysis allowed us to determine maximum race times for the drivers who had completed full races in each of the age categories. Fig. 3 shows the time intervals in which the drivers finished the races of the given round of the Rotax Max Challenge Poland Championships in 2016. The data for wet races of the first round of the Rotax Max Challenge Poland Championships in 2016 is shown separately.

2.2. *Go-kart used power analysis based on Rotax Max Challenge series*

The MicroMax Rotax Max Challenge category according to Table 1 is a category for children aged 8-10. In this category of go-karts, maximum engine power is 6 kW with engine power/rpm curve shown in Fig 4.

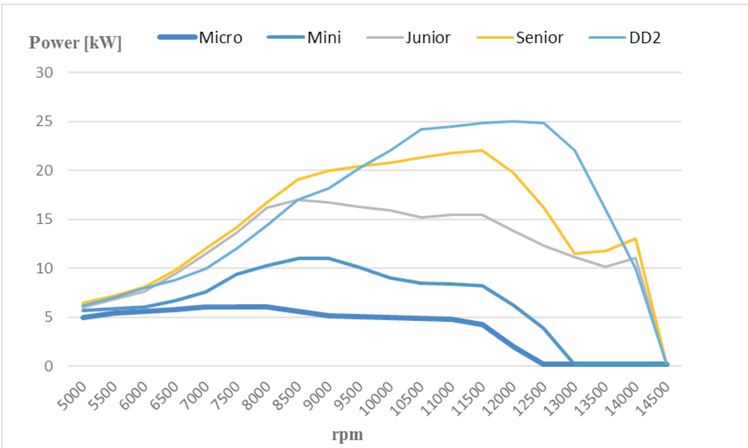

Figure 4 Rotax engine power/rpm curve for different categories

The chassis of this category is the so-called "small frame" with a wheelbase of 950 mm, with brakes only on the rear axle. Maximum race distance for this category is 14 km, which translates to a maximum race time of 12 minutes and 54.576 seconds.

The data for the analysis was collected during official races and trainings on the following tracks:

Speedworld

Go-kart Stadion

Pannónia Ring

Two lap times from the session on 12.08.2015 on Speedworld track with the configuration of 1120 m shown in Fig. 5 were selected:

1. 49,940 [s] – the fastest one,
2. 50,577 [s] – the slowest one.

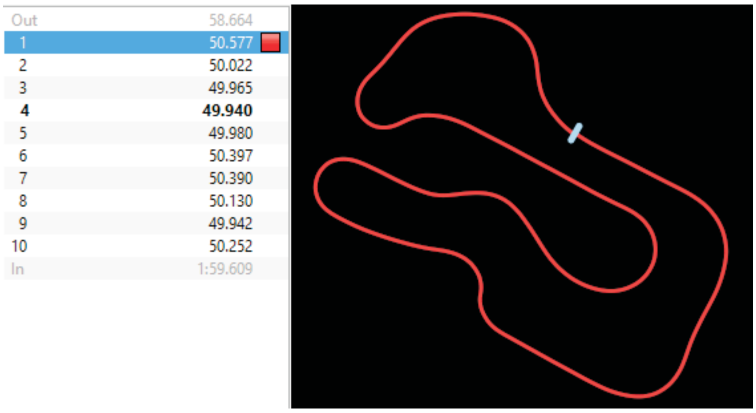

Figure 5 Race data form MicroMax category during Speedworld session 12.08.2015 and track configuration Off Camber Data tool

The power usage diagram for lap (i) and (ii) is shown in Fig. 6.

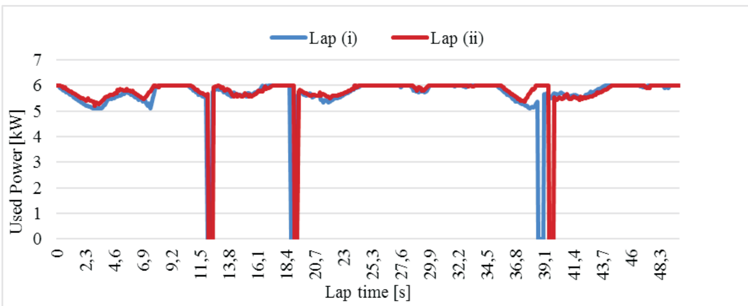

Figure 6 The power usage diagram for lap (i) and (ii) on Speedworld track, session on 12.08.2015

Based on Fig. 6, the average levels of power used for laps were calculated:

1. 5,58 [kW],
2. 5.64 [kW].

The maximum power was determined for both laps at the same level i.e. 6 kW. Further laps were selected from the following sessions on the following tracks: Gokart Stadion session on 21.06.2015 data from two laps:

1. 41,232 [s] – the fastest lap,
2. 41,760 [s] – the slowest lap.

Pannónia Ring session on 20.09.2015 data from two laps:

1. 50,626 [s] - the fastest lap,
2. 52,015 [s] - the slowest lap.

The average power value used during laps and the maximum power achieved in the MicroMax category were summarized in Tab. 2.

Table 2 Average power used and Maximum power of MicroMax category in six different laps of three sessions

	Lap (i)	Lap (ii)	Lap (iii)	Lap (iv)	Lap (v)	Lap (vi)
Average power used [kW]	5,58	5,64	5,81	5,83	5,64	5,78
Maximum power [kW]	6	6	6	6	6	6

Maximum power of electric motors for MicroMax category was defined on the level of $P_{max} = 6$ kW. Average power value used during the lap with the highest power requirements $P_{Omax} = 5,83$ kW

Knowing that the maximum race time is $t_{Rmax} =$ 12: 54,576, the work done by the MicroMax go-kart drive systems according to equation (2) W_{Rmax}:

$$W_{Wmax} = P_{omax}\, t_{Wmax} = 9,29 \cdot 0,239651 = 2,23 \text{ kWh}$$

Similar analyses and calculations were conducted for each Rotax Max Challenge category and the results are presented in condensed form.

Knowing the value of average power used during a lap for each of the categories P_{Omax} and knowing maximum race time t_{Rmax} based on Fig. 3, and chapter 2.1. Analysis of race durations in the Rotax Max Challenge Poland Championships in 2016, we calculated the work done by a running go-kart during the race with maximum energy consumption W_{rmax}. The results are presented in Tab. 4.

2.3. *Ekart – initial definition of main parameters*

Based on the analysis of go-kart power usage presented in pt. 2.2, the average power calculated based on equation (3) is assumed to be the minimum power that an eKart should generate. Maximum power for each category of eKarts is the maximum power achieved in a given age category for safety reasons. The engine power ranges for each eKart age category are shown in Fig. 7.

Table 3 Summarized sessions and laps information with average power used and maximum power on the lap for rest of Rotax Max Challenge categories i.e. MiniMax, JuniorMax, SeniorMax, DD2

	Lap (i)	Lap (ii)	Lap (iii)	Lap (iv)	Lap (v)	Lap (vi)
MiniMax						
Session	Speedworld 14.08.2015		Motodrom Vysoke Myto 12.7.2015		Pannónia Ring 28.05.2016	
Lap time [s]	46,520	47,224	49,315	50,165	49,252	50,027
Fastest/Slowes lap	Fastest	Slowest	Fastest	Slowest	Fastest	Slowest
Average power used [kW]	9,15	9,12	8,91	8,95	9,29	9,21
Maximum power [kW]	11	11	11	11	11	11
JuniorMax						
Session	Pannónia Ring 29.05.2016		Radom Track 22.05.2016		Bydgoszcz Track 1.05.2016	
Lap time [s]	47,152	48,356	32,480	33,34	46,331	46,821
Fastest/Slowes lap	Fastest	Slowest	Fastest	Slowest	Fastest	Slowest
Average power used [kW]	13,70	13,41	13,64	14,00	13,45	13,75
Maximum power [kW]	17	17	17	17	16,99	17
SeniorMax						
Session	Speedworld 21.05.2015		Pannónia Ring 19.09.2015		-	
Lap time [s]	44,086	45,597	45,786	46,532	-	-
Fastest/Slowes lap	Fastest	Slowest	Fastest	Slowest	-	-
Average power used [kW]	17,63	18,44	17,22	16,71	-	-
Maximum power [kW]	22	21,99	22	21,99	-	-
DD2						
Session	Speedworld 29.08.2015		7 Laghi Kart 16.05.2016		Pannónia Ring 29.05.2016	
Lap time [s]	56,173	57,048	49,568	51,918	45,455	46,527
Fastest/Slowes lap	Fastest	Slowest	Fastest	Slowest	Fastest	Slowest
Average power used [kW]	19,05	18,80	20,16	19,59	20,79	20,16
Maximum power [kW]	24,99	25	25	25	24,99	25

Table 4 Work done by running go-kart during the race with maximum energy consumption for every Rotax Max Challenge category

	8-10	10-13	13-16	15+	15+ gears
P_{Omax} [kW]	5,83	9,29	14,00	18,44	20,79
t_{Rmax} [mm:s]	12:54,576	14:22,744	15:31,520	17:39,315	16:41,609
[h]	0,21516	0,23965	0,25876	0,2942	0,2783
W_{Rmax} [kWh]	1,25	2,23		5,42	5,79

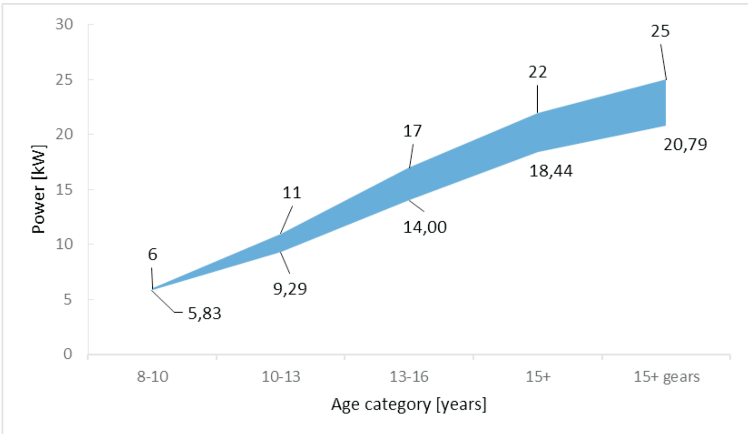

Figure 7 Power range of eKart drive system for different age categories

Knowing the work done by a running go-kart during the race with maximum energy consumption for every Rotax Max Challenge category in Table 4, we can assume to conserve the same energy for each of the age categories of eKarts.

However, in order to calculate the practical value of energy stored in batteries in accordance with equation (1) it is assumed that n should be 120%.

$$E_A = W_{Rmax} \cdot 120\% \tag{4}$$

This assumption was stated because of the necessity to provide energy for additional formation laps and potentially higher consumption during rain races. On average a rain race is longer than a race in normal conditions by 18%, see Fig. 3.

It was assumed that eKarts will be equipped with Li-Ion batteries due to their best energy-to-weight ratio [11]. Degradation of Li-Ion depends on the conditions but it is up to 10% less capacity already at 300 charging-discharging cycles and 20% at about 1000 cycles [12, 13]. Therefore it was proposed that the batteries should have 20% larger capacity than the expected E_A energy needed for an eKart race. Such a solution in addition will provide optimum, fast loading and braking capability from the first lap. The above can be described as:

$$Q_B = E_A \cdot 120\% \tag{5}$$

where:
Q_B – battery capacity [kWh].
Therefore we can rewrite Tab. 4 for the e-Kart categories as following in Table 5.

Table 5 Capacity of batteries for different age categories of eKarts

	MicroMax	MiniMax	JuniorMax	SeniorMax	DD2
Average power used by eKart on lap, P_{Omax} [kW]	5,83	9,29	14,00	18,44	20,79
Expected race time, t_{Rmax} [min:s]	12:54,576	14:22,744	15:31,520	17:39,315	16:41,609
[h]	0,21516	0,23965	0,25876	0,2942	0,2783
Work expected to be done during the race, WRmax[kWh]	1,25	2,23		5,42	5,79
Energy stored in batteries, E_B [kWh]	1,50	2,68	4,34	6,50	6,95
Capacity of batteries Q_B [kWh]	1,75	3,12	5,07	7,59	8,11

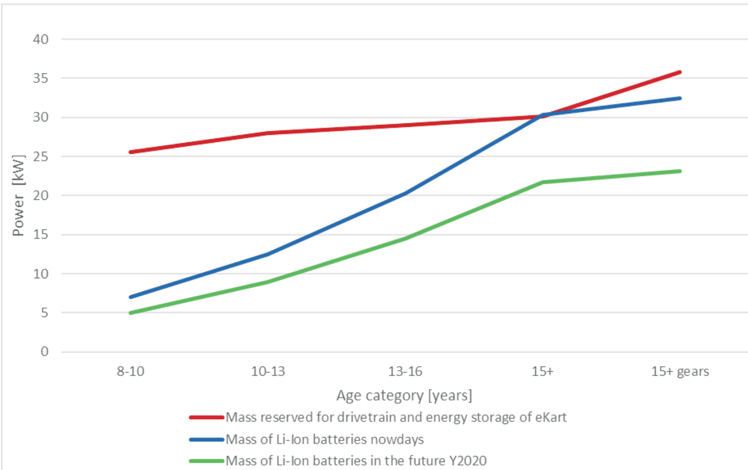

Figure 8 Maximum weight of drivetrain unit of eKart with batteries compared to potential mass of the batteries in Li-Ion technology nowadays and in 3 years' time for given age categories

An additional guideline for the selection of detailed electrical system parameters was the current weight of the go-kart in each age category. It was assumed that the weight of the eKart drive train system and the batteries should not exceed the weight of the current karts drive train system and weight of the fuel for the race shown in Tab. 1.

Based on battery capacity Q_B (5), we analyzed the options for designing eKarts for each category, within the limits of the maximum mass of the drivetrain system and the battery. We took into consideration the energy density of today's most efficient Li-Ion battery technology (250 Wh/kg) and the technology expected in three years' time (350 Wh/kg). The analysis is shown in Fig. 8.

3. Conclusions

With existing Li-Ion battery technology, it is possible to construct eKarts for children's and junior categories. Because the difference between the weight of the battery and the mass of the drivetrain unit and fuel lies between ~ 9 and ~ 19kg, it is enough for an electric drivetrain system. With the current technology, it is not possible to create eKarts for senior categories in line with the current regulations for go-karts as the mass of the battery exceeds the weight of the entire drivetrain system of the go-kart. In order to provide a solution for senior categories, it would be necessary to change the regulations, for example: race time and vehicle weight, or wait for emerging battery technology to provide an energy density of at least 350Wh / kg, which should take place within 3 years.

References

[1] **Renault, S. A. S.**: The Electric Revolution, youtube.com **2011**.

[2] **Jastrzębska, G.**: Odnawialne źródła energii i pojazdy proekologiczne, *Wydawnictwa Naukowo-Techniczne*, **2009**.

[3] **Węglarz, A. and Pleśniak, M.**: Samochód Elektryczny, *National Agency for Energy Conservation S.A.*, **2011**.

[4] **Paul Marks** *"Dawn of motorsport's electric dream" www.newscientist.com* **21.09.2011**.

[5] **Marks, P.**: Silent running: the price of a greener F1 car, *www.newscientist.com*, **2011**.

[6] **FIA,** *FORMULA ONE TECHNICAL REGULATIONS, www.fia.com/regulations*, **2009**.

[7] http://www.formula1-dictionary.net , Audi R18 e-tron Quattro Flywheel KERS Hybrid System, **2012**.

[8] **Jacob, J., Colin,J. A., Montemayor, H., Sepac, D., Trinh, H. D., Voorderhake, S. F., Zidkova, P., Paulides, J. J. H., Borisaljevic, A. and Lomonova, E. A.**: InMotion hybrid racecar: F1 performance with LeMans endurance, *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering,* **2015**.

[9] **FIA,** http://www.fiaformulae.com, **2017**.

[10] **BRM** http://www.rotax-kart.com/en/Products/MAX-Engines/ **2017**.

[11] **Van Noorden, R.**: A Better Battery - Chemists are reinventing rechargeable cells to drive down costs and boost capacity, *Nature*, 507, 6, **2014**.

[12] **Xu, B., Oudalov, A., Ulbig, A., Andersson, G. and Kirschen, D. S.**: Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment, *IEEE Transactions on Smart Grid,* **2016**.

[13] **Lawder, M. T., Northrop, P. W. C. and Subramanian, V. R.**: Model-Based SEI Layer Growth and Capacity Fade Analysis for EV and PHEV Batteries and Drive Cycles, *Journal of The Electrochemical Society,* 14, **2014**.