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Reducing emissions of harmful substances in rally cars

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This article describes the issue of reducing exhaust emissions in rally cars. The issue of currently used exhaust gas aftertreatment systems is described, as well as the potential possibility of reducing emissions of harmful substances while driving on special sections. Statistical calculations were also carried out regarding the emissions of harmful substances by rally cars during the entire season of the Polish Rally Championship.

Key words: *internal combustion engines, catalytic converters, harmful substances, motorsport, car rallies*

1. Introduction

Motorsport have a history not much shorter than the car itself. Carl Benz patented his first vehicle in 1886, and the first car race took place in France 8 years later in 1894 on the Paris-Rouen route. People's tendency to compete and the desire to achieve the best possible results was the driving force behind the development of motorsports and, consequently, automotive technology. It is important to remember that many of the solutions originally used in performance cars were later adapted for use in their mass-produced counterparts [14]. Features such as double overhead cam timing (DOHC), turbocharging, four-wheel drive, disc brakes, anti-lock braking system (ABS), active suspension and even rear-view mirrors, even if they do not have their roots in motorsport, deserve recognition for their refinement and popularization in mass-produced cars. The extreme nature of competition in motor sports also allows us to obtain answers about the limits of reliability of individual components that would never be operated in such demanding conditions. Motor sports, in addition to providing a development impulse for the automotive industry, have been an object of interest for fans for many years. Both circuit racings, i.e.: FIA Formula One World Championship (F1), FIA World Endurance Championship (WEC), FIA World Touring Car Cup (WTCR) and rallies of various ranks, i.e.: FIA World Rally Championship (WRC), FIA European Rally Championship (ERC) attract the attention of the public both on race tracks and on special stages of rallies. In the case of rallies, the competition covers a much larger area than in the case of circuit racing. At the same time, in the case of rallies, fans can stay much closer to rally cars than in the case of circuit racing, because places such as the start and finish of the rally, regroups, service parks attract interest, and rally cars are within these zones easy to reach for them. In addition to fans, there is also a large group of people from the organizing committee and members of motor sports teams. Both racing and rally cars, like mass-produced cars, emit noise and harmful substances. The least advantageous in this respect is the internal combustion engine drivetrain, hybrid solutions are an intermediate solution, and electric drive systems are the most advantageous. However, these assumptions do not take into account the entire vehicle life cycle, which is increasingly turning out to be much less favourable for electric drive systems. Moreover, currently the Battery Electric Vehicle (BEV) drive system, or more precisely the battery that is the energy source, is so imperfect that this type of drive is unable to enable the car equipped with it to compete with cars equipped with a combustion or hybrid drive. At the same time, electrically powered cars are much more expensive than their combustion counterparts, and safety issues, which are of great importance in motor sport, are much more complicated. Given the above, the internal combustion engine is currently optimal for motorsport and, assuming it continues to be used there, efforts should be made to improve it in terms of noise and emissions. However, it should also be emphasized that reducing noise emissions in motor sport is not always desirable for safety reasons. The noise emitted by a rally car while driving on a special stage makes it easier for fans to recognize an approaching car. Therefore, reducing noise emissions in motor sports is not always desirable for safety reasons and an appropriate compromise must be reached. For this reason, the article will discuss issues related to harmful substances emitted by rally cars. It should be emphasized that the review of the scientific literature indicates gaps in the approaches to the topics discussed in the article. According to the research conducted by the authors, the topic of exhaust gas treatment in cars is the subject of many scientific publications, but not in the case of motor sports. Hence, according to the authors, there is a need to fill this gap, which was the reason for conducting the research described in this article.

2. The impact of harmful substances on human health

Emission of harm substances from passenger cars is a serious problem that negatively affects both human health and the natural environment. A list of harmful substances found in car engine exhaust gases and their negative disease effects is summarized in Table 1.

Table 1. List of harmful substances

Particle	Influence on human health
Particular Matter (PM_{10} and $PM_{2.5}$)	The effect of PM (including black carbon) on the incidence of cardiovascular disease, respiratory disease, lung cancer and mortality due to them as well as total mortality has been shown [8, 19].
Hydrocarbons (HC)	The research indicates a substantial elevation in the risk of Chronic Obstructive Pulmonary Disease (COPD) when individuals are exposed to high levels of environmental Hydrocarbons (HC). Moreover, there is a notable connection to systemic inflammation in this progression. In the context of short-term effects, studies within school populations have identified a decline in lung function, heightened instances of airway inflammation, and an escalated likelihood of developing lung cancer among those consistently exposed to HC over an extended period [10, 17].
Nitrogen oxides (NO_x)	Recent meta-analyses have shown an association between the concentration of NO_2 and mortality from all causes, including lung cancer and respiratory and cardiovascular diseases. Short-term exposure to NO_2 results in an increase in exacerbation of chronic respiratory diseases and bronchial reactivity in people with pre-existing lung disease [1, 4, 5].
Carbon monoxide (CO)	Generally, epidemiological studies revealed that short-term exposure to ambient carbon monoxide is linked to all-cause mortality and cardiovascular diseases [11, 13]. People with heart conditions can be particularly affected by CO causing chest pain and affecting the ability to exercise. Exposure to high concentrations of CO cause vision problems, reduce ability to work, reduced manual dexterity, and difficulty performing difficult tasks. Very high concentrations of CO can cause death [15]. Exposure to ambient CO was associated with the increase in risks for the total number of respiratory diseases such as bronchiectasis, pneumonia, and asthma [18].

All the above-mentioned harmful substances, especially with long-term exposure, have a negative impact on human health. For this reason, just like the automotive industry, motor sports also consistently attach importance to reducing emissions of harmful substances from combustion engines. Various solutions are used, including: the use of exhaust gas treatment systems, or, as mentioned earlier, changing the way the car is propelled. As in the case of mass-produced cars, in motorsport there is no single best answer to the question of what the drive system of the future should look like. Many different drivetrain concepts match those found in mass-produced cars and often go a step further. Hybrid drivetrains are used in various configurations in cars such as Rally1 in rallies, LMP1-Hybrid in long-distance circuit racing, or FIA Formula One World Championship (F1), as well as purely electric drivetrains in Formula E and FIA eTouring Car World Cup (ETCR). Alternative fuels for combustion engines are also used, the main purpose of which is not to reduce emissions of harmful substances, but can be included in activities aimed at making motorsport more environmentally friendly. The topic of the future of drive systems in sports cars is currently also discussed in rallies, where hybrid drivetrains have begun to be implemented in Rally1 cars [7], and in the case of combustion engines, alternative fuels have been introduced. P1 fuel is a synthetic fuel, CO_2 neutral and fossil fuel free. Development work is also underway on hybrid systems for lower groups of rally cars, i.e. Rally2/3/4/5 [16]. It should be emphasized, however, that at the moment, for reasons such as: availability of technology, ability to ensure safety, price-performance ratio, the optimal source of drive in motor sports is still the combustion engine. With this in mind, we should focus on how to clean exhaust gases from such engines.

3. Reducing the emission of harmful substances in rally cars

3.1. On the road sections

Regulations governing use of catalytic converters in motorsport have existed since the 1980s. The overarching document defining the rules of competition in motorsport and the technical regulations of cars is the International Automobile Federation (FIA) International Sporting Code (ISC). In art. 252 App. J 2023 to the FIA ISC stipulates that a rally car must be equipped with an original or homologated catalytic converter indicated in FIA Technical List No. 8, if such are the requirements of the country in which the competition is held [6]. Some of the more technically advanced groups of rally cars must use FIA-approved catalytic converters. This is since in groups such as Rally1, Rally2, Rally3, Rally4 or Rally5 it is permissible to change the engine to an engine other than the original one that has FIA homologation. In such a case, the catalytic converter that a given car model was originally equipped with will most likely no longer meet the requirements, because the parameters of the engine used will be completely different from those of the originally installed one. Modifications to the engine in which a car is equipped, or even replacing it with another one, include the reasons why the FIA provides for the homologation of catalytic converters intended for use in motor sports, including rallies. The catalytic converter homologation process according to the FIA procedure is delegated to the FIA National Sporting Authorities (ASN) [2]. In the case of Poland, ASN is the Polish Automobile and Motorcycle Federation (PZM). The ASN catalytic converter homologation procedure includes the following steps [2]:

- The catalytic converter is approved for a given engine capacity and a group of cars with a specific scope of modifications.
- The cross-section of the catalytic insert must be min. 100 CPSI, and its dimensions depend on the power of the engine with which they are to work.
- The minimum conversion efficiency of individual toxic substances, i.e. CO, HC and NO_x, is specified and must be met during approval tests.
- Approval tests are carried out following the ECE R15 Type I cycle.
- Tests must be performed in an independent testing laboratory.

The analysis of the actual situation shows that the catalytic converter, homologated by the FIA regulations, is not approved for a specific car model, but for the range of engine capacity and modifications of a given group of cars.

This is intended to increase the universality of catalytic converters homologated by the FIA procedure, which is key to ensuring their acceptable selling price in the case of relatively small production series occurring in motorsport. The maximum emission levels of harmful substances were not specified for homologation tests, but the minimum catalytic converter efficiencies for individual harmful substances were provided. This approach results from the need to ensure the already mentioned universality of catalytic reactors in motorsport. When, after passing the above procedure, the catalytic converter is approved, it is entered on the FIA Technical List No. 8, so it can be used in rally cars. It should be installed in a rally car in accordance with the manufacturer's guidelines so that the efficiency of the catalytic converter required by regulations is maintained.

In the discussed case, a catalytic reactor prepared by M-Sport Poland was tested. It was installed in a 2018 Ford Fiesta ST (presented in Fig. 1) test car in accordance with the requirements of the FIA Catalytic Converter Homologation Regulations.

Fig. 1. Ford Fiesta ST

Table 2 presents the basic technical data of the above-mentioned car.

Table 2. Basic technical data of the Ford Fiesta ST

Parameter	Unit	Value
Weight of the car	kg	1262
Engine type	–	Turbocharged, petrol
Number of cylinders	–	3
Displacement	cm^3	1496
Maximum power	kW	147
Maximum torque	Nm	290
Transmission	–	Six speed manual

The tests were carried out on a chassis dynamometer AVL Zoelner 48” 2WD at a BOSMAL Automotive Research and Development Institute Ltd and the emissions of harmful substances were recorded by the exhaust emission analysis system AVL AMA i60 and CVS system AVL i60 LD LE. Exhaust emissions were measured before and after the catalytic converter. The tests were carried out in accordance with the procedure according to the ECE-R15 Type 1 driving cycle, also known as UDC (Urban Driving Cycle). The ECE-R15 Type I cycle is shown in Fig. 2.

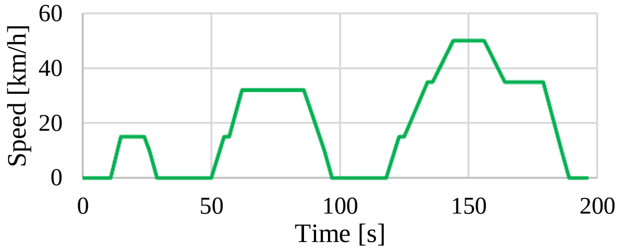

Fig. 2. ECE-R15 Type 1 cycle

The ECE-R15 Type I cycle is an urban driving cycle that was introduced in 1970. Later, after minor modifications, it became part of the EUDC extra-urban driving cycle, the ECE-R101 regulations introduced in 1990, and part of the NEDC cycle used until 2017. It was then replaced by the WLTC cycle [12]. The ECE-R15 type 1 cycle represents low-speed driving in large European cities. The FIA's motivation for choosing this particular driving cycle for testing catalytic converters used in motor sports can be explained by the fact that the main objective in motor rallies is to reduce emissions on the road sections, which constitute approximately 75% of the entire rally route. The average speed on road sections is set so that crews can cover a given section in accordance with road traffic regulations.

The efficiency of the catalytic converter as defined in the FIA regulations can be described (1):

$$K_{(X)} = \frac{Y_{(X)} - Z_{(X)}}{Y_{(X)}} \cdot 100\% \quad (1)$$

where: K(X) – catalytic converter efficiency, X – selected toxic component of exhaust gases, Y – mole fraction of X upstream of the catalytic converter, Z – mole fraction of X after the catalytic converter.

In accordance with the FIA procedure, tests of CO, HC and NO_x mole fractions were carried out both before and after the catalytic converter. The research results were obtained and are presented in Table 3.

Table 3. Results of tests on the efficiency of the catalytic converter

Particle	Pre-cat [g/km]	Post cat [g/km]	$K_{(X)}$	$K_{(X)}$ required by the FIA
CO	6.512	0.198	97.0%	75%
HC	3.288	0.011	99.7%	N/A
NO_x	0.770	0.024	96.9%	N/A
HC + NO_x	4.058	0.035	99.1%	60%

As it can be noted, the catalytic converter met the FIA efficiency requirements. It is interesting to compare the obtained results with the applicable EURO exhaust emission standards [12]. A summary of the maximum emission levels of individual harmful substances is presented in Table 4 below.

Table 4. Maximum emission levels for given Euro standard

	CO [g/km]	THC + NO_x [g/km]	THC [g/km]	NO_x [g/km]
Euro 1	2.72	0.97	–	–
Euro 2	2.2	0.5	–	–
Euro 3	2.3	–	0.2	0.15
Euro 4	1	–	0.1	0.08
Euro 5	1	–	0.1	0.06
Euro 6	1	–	0.1	0.06

Comparing table values from the results presented in Table 3, it can be concluded that the tested car equipped with a catalytic converter approved by the FIA, taking into account the emission of harmful substances, would meet standards up to and including Euro 6. It should be emphasized that these emission values cannot be directly compared. In the case of Euro standards, the homologation testing procedure is different than in the case of the FIA standard, which specifies the test cycle according to ECE R15 Type 1, and not NEDC, WLTP or RDE. However, the ECE-R15 Type 1 Urban Driving Cycle is the least favourable case in terms of emissions (variable engine loads, including stops) [3, 9], it is possible to analyse the amount of harmful substances emitted by rally cars with and without exhaust aftertreatment systems on road sections. It should be emphasized here that the engine maps of modern rally cars are calibrated separately for road sections and separately for special stages. Thanks to this, if full engine operation is not required on the access section, the map can meet the conditions ensuring optimal operating parameters of the catalytic converter. The main such parameter is the excess air coefficient λ. For λ = 1, the catalyst is characterized by the highest NO_x reduction efficiency and high CO and HC oxidation efficiency.

Taking into account the above results, it was decided to carry out statistical calculations regarding the emissions of harmful substances during the PZM Polish Rally Championship (RSMP) season for two cases. In the first case, the emissions of harmful substances throughout the season were analysed for one car, while in the second case, the average number of crews entered in the rally was analysed. All rallies in the PZM RSMP season were included in the analysis. In the 2023 season, they consisted of rallies with the lengths specified in Table 5. The emissions of individual harmful substances were compared without a catalytic converter and with a catalytic converter installed in the car.

Assuming the above distances, it was possible to estimate the emissions of harmful substances from the entire RSMP season in two versions. In the first case, rally cars are not equipped with a catalytic converter approved by the FIA, while in the second case it is installed in the car. It should be noted that the following analyses assume that all rally cars are the same and are equipped with the same catalytic converters. However, this simplification seems to be good enough for statistical analysis, because the Rally3 group cars are in the middle of rally cars groups in terms of generated power. This should also translate into the average amount of fuel burned and, consequently, the emission of harmful substances for the entire group of rally cars.. The results obtained for one car based on calculations are presented in Fig. 3.

Table 5. Route characteristics in the Polish Rally Championship season 2023

No.	Rally	Road Sections, [km]	Special Stages, [km]	Total, [km]
1.	51. Rajd Świdnicki	261.20	132.60	393.80
2.	79. Rajd Polski	737.41	182.06	919.47
3.	42. Rajd Podlaski	418.48	110.60	529.08
4.	Rajd Małopolski	202.88	118.18	321.06
5.	32. Rajd Rzeszowski	445.12	152.94	598.06
6.	Rajd Śląska	484.78	150.34	635.12
7.	68. Rajd Wisły	364.25	124.36	488.61
Total:		2914.12	971.08	3885.20

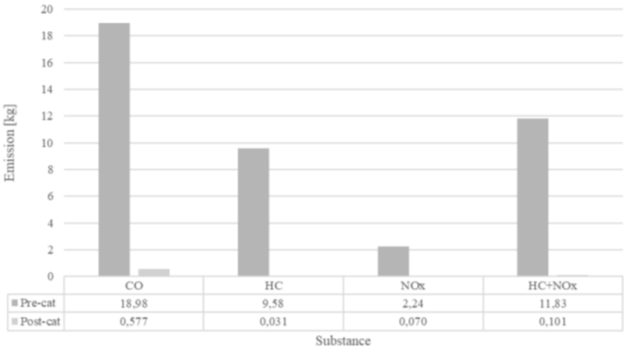

Fig. 3. Results of emissions of harmful substances on road sections for the entire RSMP season for one rally car

Moreover, by assuming the average number of starting cars in the RSMP based on the average number of entries from all rounds, which is 47 crews, it was possible to estimate how many harmful substances the RSMP rallies emits on the road sections throughout the season. The results are presented in Fig. 4.

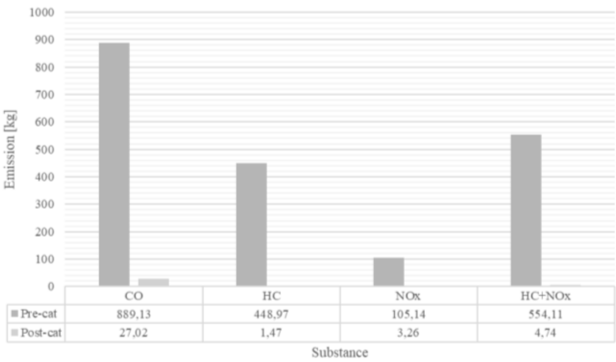

Fig. 4. Results of emissions of harmful substances on approach sections for the entire RSMP season for the average number of rally cars

The graphs show the significant impact of the catalytic reactor on reducing the emission of harmful substances. The difference between a car equipped with a catalytic converter and a car without it is significant, because for each of the harmful substances the reduction in their amount reaches almost 100%, in each case exceeding 97%. The presented data well justify the need to use exhaust gas treatment systems in rally cars. Even taking into account the relatively small number of rally cars that are only on the road temporarily during sporting events. It should be noted that the tested catalytic converter significantly exceeded the standards set by the FIA, which means that it stood out positively from the regulations in force in motorsport. Comparing the obtained analysis results with the situation of all road transport in Poland, in the case of CO the entire emission season of rally cars is given in Table 4. In the case of CO, it is 0.09 ‰ of this emission, and NO_x 0.02 ‰. As it can be noted, rallies constitute a marginal part of road transport in Poland.

3.2. On the special stages

Special stages of a car rally have different characteristics than road sections. Driving on a special stage is a time trial, so the crews try to achieve the shortest possible travel time. In such conditions, the engine of a rally car works almost all the time under full load. The amount of fuel burned in this case is much higher than when driving on the road section. Additionally, rally cars use the Anti-Lag System (ALS), whose task is to maintain a constant, high turbocharger speed when the foot is taken off the throttle pedal by fuel injection at these moments. Apart from the fact that ALS undoubtedly has a positive effect on the performance of a rally car, it also has a negative impact on fuel consumption and an increase in engine operating temperature in engines with an exhaust manifold integrated with the head. Higher fuel consumption directly translates into increased emissions of harmful substances, so it is worth considering replacing the ALS system with another one that will translate into increased fuel consumption to a lesser extent, or preferably none at all.

To show the benefits that can be obtained by replacing the ALS system with another one, tests were carried out during which the Fiesta ST Rally3 (model presented in Fig. 5) built by M-Sport Poland moved along a designated route in 3 modes, i.e.: ALS off, ALS at the highest level of turbocharger support (ALS3) and ALS at an intermediate level of turbocharger support (ALS2). The data was recorded by a data acquisition system installed in the car. Table 6 presents the basic technical data of the above-mentioned car.

Fig. 5. Ford Fiesta ST Rally3

Table 6. Basic technical data of the Ford Fiesta ST Rally3

Parameter	Unit	Value
Weight of the car	kg	1210
Engine type	–	Turbocharged, petrol
Number of cylinders	–	3
Displacement	cm^3	1496
Maximum power	kW	158 (FIA 30 mm restrictor)
Maximum torque	Nm	400
Drivetrain	–	Constant four-wheel drive
Transmission	–	Five-speed sequential gearbox

Based on the tests performed, fuel consumption results were obtained depending on the ALS system used. They are presented in Fig. 6.

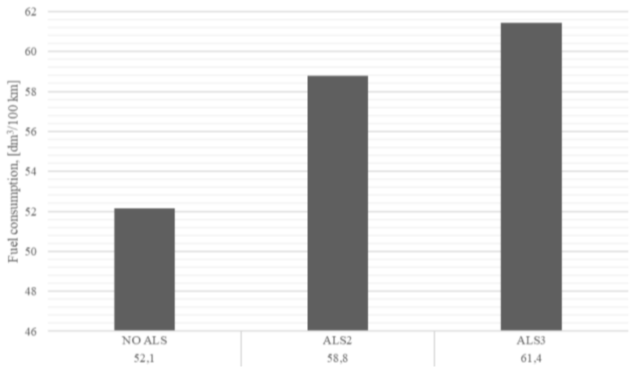

Fig. 6. Comparison of fuel consumption for different levels of ALS operation

As can be seen, the difference in fuel consumption by a rally driver on a special stage with the ALS system on and off can be up to 9.3 dm^3/100 km. Even the intermediate ALS mode increases fuel consumption by 6.6 dm^3/100 km. A comparison of fuel consumption on Special Stages throughout the RSMP season was made, in accordance with Table 5. As a result of the calculations, fuel consumption values per car and the average number of cars entered in the rally were obtained and are presented in Table 7.

Table 7. Calculated fuel consumption for the entire RSMP season for the average number of rally cars (47)

	NO ALS	ALS1	ALS2
Fuel consumption per 1 car, [dm^3]	506.37	570.92	596.53
Fuel consumption per 47 cars, [dm^3]	23,799.58	26,833.26	28,037.12

Analysing the entire RSMP rate in accordance with the adopted assumption, i.e. assuming the average number of registered crews throughout the entire season 47, savings in fuel consumption without the use of the ALS system may amount to approximately 15%. This is an important value, especially since reducing fuel consumption will also reduce emissions of harmful substances from rally cars.

In the article devoted to alternative 48 V drive systems in rally cars, the issue of using an electrically driven compressor was raised [16]. Such a device would allow, to some extent, to provide the required boost pressure in a situation where the turbocharger does not have the required rotational speed. Thus, thanks to the use of such a device, it would be possible to limit the operation of the ALS system, which would result in achieving the assumed goal, i.e. reducing fuel consumption and, consequently, harmful substances consumed by the rally car. while driving on the Special Stage. The next step will be to test a rally car engine equipped with an electrically driven compressor. The conclusions will allow, at least initially, to answer the question to what extent it will be possible to limit the use of the ALS system in a rally car.

4. Summary

Due to the recent change in the Euro 7 standard, combustion engines, also in small cars, which are the basis for building rally cars, will remain available for at least a few more years. Moreover, in the case in question, i.e. rally cars powered solely by electricity with an energy source in the form of batteries, there is a significant difference in the performance of the cars in favour of cars equipped with combustion engines. With this in mind, it seems crucial to improve combustion engines in order to reduce emissions of harmful substances, including fuel consumption, rather than to completely abandon them. On the one hand, there are options regarding exhaust gas treatment systems, which, as presented in this article, allow for:

- reducing emissions of harmful substances such as CO, HC and NO_x by over 96% depending on the substance.
- in the scale of the entire analysed RSMP season, this shows the large scale of this action, which can be counted in hundreds of kilograms when it comes to reducing emissions from the entire rate.

However, it should be borne in mind that exhaust gas treatment systems have a negative impact on engine parameters, which are crucial in car rallies, so this should be taken into account when implementing them.

On the other hand, in addition to exhaust gas treatment systems, the possibilities of using electrical devices can also be used, thus creating hybrid drive systems. Reducing fuel consumption also directly reduces the emission of harmful substances. For this reason, work is being carried out to verify the effect of using a 48V hybrid system consisting of BISG and an electric compressor. The next direction of work should be further tests of the above solutions in conditions similar to those of a real rally.

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Nomenclature

ABS	anti-lock braking system
ALS	turbocharger anti lag system
ASN	national sporting authority
BEV	battery electric vehicle
CPSI	cells per square inch
DOHC	double overhead camshaft
ECE	United Nations Economic Commission for Europe
ERC	FIA European Rally Championship
ETCR	FIA Etouring Car World Cup
F1	FIA Formula One World Championship
FIA	International Automobile Federation
ICE	internal combustion engine
PZM	Polish Automobile and Motorcycle Federation
RDE	real driving emissions
RSMP	Polish Rally Championship
UDC	urban driving cycle
WEC	FIA World Endurance Championship
WLTP	worldwide harmonised light vehicle test procedure
WRC	FIA World Rally Championship
WTCR	FIA World Touring Car Cup

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