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MULTIFRACTAL ANALYSIS VEHICLE'S IN-USE SPEED PROFILE FOR APPLICATION IN DRIVING CYCLES

MULTIFRAKTALNA ANALIZA EKSPLOATACYJNEGO PROFILU PRĘDKOŚCI POJAZDU W ZASTOSOWANIU DO TESTÓW JEZDNYCH*

Time signals recorded by the on-board diagnostic system (OBD), describing the manner of vehicle's movement in actual road conditions show non-stationarity and non-linearity, as well as statistical multiscalarity. In practice, it means that the analysis of registered time series requires modelling of non-linear phenomena. The aim of this study was to examine the nature of the vehicle speed profile in actual road conditions with the method of multifractal analysis. A number of studies indicates that the driving tests applied for many years have not been representative for the actual operating conditions of vehicles. For both the new Worldwide Harmonised Light duty Test Cycle (WLTC), a worldwide harmonised procedure of light vehicle testing, as well as in actual urban driving conditions along the measuring route, being subject to empirical research, confirmation of strong multifractal properties of the recorded vehicle speed time series have been obtained.

Keywords: *multifractal analysis, driving cycles, actual road conditions.*

Sygnały czasowe rejestrowane przez system diagnostyki pokładowej OBD i opisujące sposób ruchu pojazdu w rzeczywistych warunkach drogowych, wykazują niestacjonarność i nieliniowość oraz statystyczną wieloskalowość. W praktyce oznacza to, że analiza zarejestrowanych szeregów czasowych wymaga modelowania zjawisk nieliniowych. Celem niniejszej pracy było zbadanie charakteru profilu prędkości pojazdów w rzeczywistych warunkach drogowych metodą analizy multifraktalnej. Szereg badań wskazuje, że stosowane przez wiele lat testy jezdne nie były reprezentatywne dla rzeczywistych warunków eksploatacyjnych pojazdów. Zarówno dla nowego cyklu jezdnego WLTC, światowej zharmonizowanej procedury badań pojazdów lekkich jak i w rzeczywistych warunkach drogowych jazdy miejskiej na trasie pomiarowej, będącej przedmiotem badań doświadczalnych uzyskano potwierdzenie silnych własności multifraktalnych rejestrowanych szeregów czasowych prędkości pojazdu.

Słowa kluczowe: *analiza multifraktalna, testy jezdne, rzeczywiste warunki drogowe.*

1. Introduction

Tests of the performance of automotive drive systems find application in the phase of concept development (basic cognitive research), in the design phase (as part of prototype testing), in the production phase (during quality control), at the admission stage (type approval tests) and in the maintenance phase (diagnostic tests). This goal is attained through various types of examination at engine test stands, which differ with regard to the stipulated working conditions. This work undertakes to address the problem of analysing the in-use vehicle speed profile with the view to applying it to driving tests. The Vehicle Driving Cycle (VDC) is a time series of data representing vehicle speed, which is intended to reflect a vehicle's movement in real road conditions and be used in evaluation of a vehicle or engine in terms of its economy and emissions.

Many years of research have led to several hundred practical driving cycles in various countries and regions. Most of the current tests used to determine emissions of motor vehicles are developed in accordance with the principle of accurate simulation in the time domain. The most popular tests are ones like FTP-75 (Federal Test Procedure), NEDC (New European Driving Cycle) or JC08 (Japanese cycle). NEDC is used in Europe, the FTP 75 cycle is used in the United States and JC08 in Japan. NEDC is a synthetic cycle of the theoretical driving profile, while the other two come from actual usage data [3, 9].

More reliable results for fuel economy during the simulation of vehicle operating conditions at engine test stands are to be provided by the WLTC test (Worldwide Harmonised Light duty Test Cycle), which is a result of the world-wide harmonised light vehicle testing procedure. The cycle is based on actual driving profiles derived from statistical research [18].

Each methodology for creating driving tests requires an analysis of the nature of recorded in-use driving speed signals. Most of the actual time signals, including the time series recorded by the on-board diagnostic system (OBD) and describing the way the manner of vehicle movement in actual road conditions, show non-stationarity and non-linearity as well as statistical multiscalarity. In practice, it means that the analysis of recorded time series requires the use of non-linear analysis methods [1, 7]. The methods of multifractal formalism using local power measures, such as Holder signal regularity exponents or probabilistic indicators, are a good way of modelling the dynamics of such systems [5, 8].

The Holder singularity exponent, determined at each point where the function is defined, reflects the level of amplitude fluctuation in the vicinity of this point. The scaling factor of the probabilistic meas-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** ure distribution function, based on the values of the signal amplitude, allows for segmentation with considerations for the level of entropy. The statistical distribution represented by the histogram of singularity exponents is a picture of the multifractality of the signal. There are two ways to determine the multifractal spectrum of a singularity exponent. The direct method relies on the approximation of the histogram for determined Holder exponents. The indirect method in which the fractal dimension is usually assumed to be the capacitive dimension of the curve being a graph of the signal considered, is based on the algorithm of detrended fluctuation analysis of time series [6].

The article presents the following issues. Chapter 2 signals the idea of the applied multifractal analysis method. The results of this analysis for the driving cycle of the harmonised light vehicle test procedure (WLTC) are presented in Chapter 3. The tests carried out in actual urban driving conditions are discussed in Chapter 4. Chapter 5 constitutes the concluding section.

2. Multifractal formalism and the regularity measure of a time series

Multifractal formalism has found a number of applications in the analysis of real signals, in particular in performance diagnostic tests of motor vehicles [4,11-17]. The conducted research indicates various procedures for identifying the multifractal nature of actual time series.

This chapter presents an approach based on the exponents of signal singularities and multifractal spectrum. The point exponent of Holder singularity function $f(x)$ in point x_0 denotes the number h defined as the supremum of all exponents satisfying, for a certain C> 0, the condition:

$$\left|f(x)-P_n(x-x_0)\right|\leq C\left|x-x_0\right|^h \tag{1}$$

where $P_n(x-x_0)$ is a polynomial of $n<h$ degree. The relationship shows that the exponent $h>1$ describes the regularity of a function more accurately than its subsequent derivatives. If the signal representation is a time series $f_i, i=1,2,\ldots,N$, then:

$$f_{i+\Delta i}-f_i \sim \left|\Delta i\right|^{h(i)} \tag{2}$$

where $h(i)$ is the singularity exponent of time series at point i.

A set of fractal dimensions for each subset of time series elements f_i with the same Holder exponent h creates a multifractal spectrum of singularity. To determine the spectrum of Holder exponents, vehicle speed signals recorded by the OBD system we used a multifractal version of the detrending fluctuation analysis (MF-DFA) based on the elimination of the trend from the tested time series. The procedure leads to determining the measure in the form of a fluctuation function of row q exhibiting a power character:

$$F_q(s)\sim s^{H(q)} \tag{3}$$

where $H(q)$ is a generalised Hurst exponent, and the parameter q allows for decomposing the measure with regard to its value. Legendre's transform of generalised large-scale exponent $\tau(q)=qH(q)-1$ allows for obtaining a multifractal spectrum:

$$f(h)=qh-\tau(q) \tag{4}$$

where $h=\frac{d}{dq}\tau(q)$ is Holder singularity exponent.

The multifractal spectrum constitutes a histogram of exponents reflecting the level of signal amplitude fluctuation. Moreover, the parallelism of multifractal formalism and statistical thermodynamics indicates that Holder singularity exponent and the multifractal spectrum can be interpreted as the energy and entropy of the studied process respectively.

The description of the system's dynamic properties based on the multifractal spectrum of the time series is permitted by:

- the level $\Delta=h_{max}-h_{min}$ of multifractality determined by singularities with the largest and smallest time series fluctuation of the observed signal h_{min} and h_{max},
- singularity with the largest dimension, that is the most common time series singularity $\{h_0 : f(h_0) = \max f(h)\}$,
- the dimensional range of singularity subsets $\Delta f=f(h_{max})-f(h_{min})$.

3. Simulation research of the WLTC test

A number of studies have confirmed that the driving tests used for many years are not representative for the actual operating conditions of vehicles. As a result, the emission and fuel consumption of vehicles are underestimated. Striving for a more dynamic, harmonised test cycle, a new WLTC (Worldwide harmonised Light duty Test Cycle) has been developed. The synthesis was made on the basis of data on traffic parameters in Europe, India, Japan, Korea and the USA, taking into account situations related to driving in urban, countryside and motorway traffic. Compared to NEDC, the test cycle is longer, significantly more dynamic and features a lot more acceleration and deceleration cycles, shorter stops and higher average and maximum speed values. Due to the introduced changes, the WLTC driving cycle will provide much more accurate conditions for calculating fuel consumption and exhaust emissions [10]. Its first application will apply to vehicle models introduced to the market for the first time since September 2017. The WLTC driving cycle has been divided into four parts, corresponding to different driving speeds: low, medium, high and extra high. If the maximum speed does not exceed 135 km/h, then part of extra high speed should be replaced with part of the low speed. The WLTC time series for 3b class cars, with the power to weight ratio of PWr> 34, is shown in Fig.1, and its basic parameters in Table 1. The drive dynamics in the case of these vehicles is determined by the driver's behaviour and the intensity of the road traffic, not by the car's technical parameters.

Singularity spectra for the studied WLTC driving test shown in Fig. 2, confirm its multifractal nature. The level of multifractality is: $\Delta=7{,}92$, while the dimensional range of segments with the highest and lowest probability $\Delta f=0{,}92$. The most common singularity exponents refer to those fragments of recorded time series which describe the greatest variability. In turn, the lowest probability of recording is shown by the drive periods of the highest regularity. Most of the points are concentrated around the dimensions corresponding to the singularities with the largest and smallest fluctuation of vehicles speed time series.

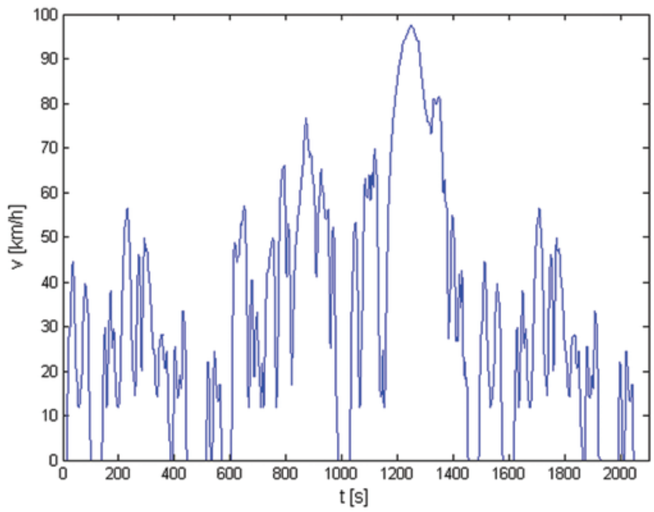

Fig. 1. WLTC driving cycle

Fig. 3. CarChip Pro Recorder in a vehicle's OBD slot

Table 1. Basic parameters of the WLTC cycle for Class 3b vehicles

Phase	Duration	Stop duration	Distance	p_stop	v_max	a_min	a_max
	s	*s*	*m*		*km / h*	m / s^2	m / s^2
Low	589	156	3095	26.5 %	56.5	-1.47	1.47
Medium	433	48	4756	11.1%	76.6	-1.49	1.57
High	455	31	7162	6.6%	97.4	-1.49	1.58
Extra-High	323	7	8254	2.2%	131.3	-1.21	1.03
Total	1800	242	23 266				

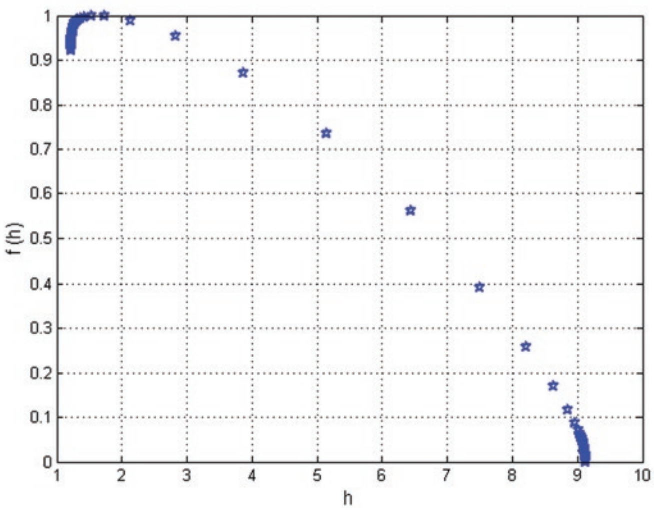

Fig. 2. The singularity spectrum for the WLTC driving test

4. Research and analysis of empirical data

The article presents the results of vehicle traffic tests in actual road conditions, represented by urban driving in a large agglomeration, between 9 am and 1 pm for five working days. The conducted analysis was based on vehicle's speed time series with a sampling period equal to 1s.

The applied measuring device, shown in Fig. 3 is capable of sampling the speed once every second. The range of speeds available for recording is 0 -255 km/h, with a resolution of 1 km/h while the maximum recordable research distance is 16,000 km. The device has the ability to record a number of other operating parameters, such as engine speed, vehicle acceleration, pressure in the inlet manifold, and throttle position and allows communication with the engine governing unit using the following communication protocols: J1850-41,6, J1850-10,4, ISO9141, KWP2000 (ISO 14230), CAN (Control Area Network ISO 11898).

The measuring route consisted of a 12-kilometre-long road section and ran between Plac Wilsona and the Galeria Mokotów in Warsaw. The map presenting the measurement route, developed with the use of Google maps, is shown in Fig. 4.

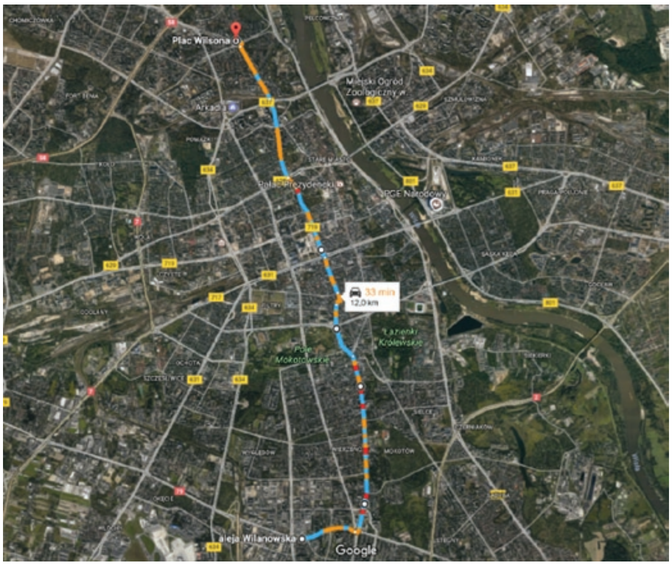

Fig. 4. Map showing the measurement route

Examples of speed change pattern recorded during one day for two-way trips are shown in Fig. 5. The conducted analysis was based on the vehicle's speed time series with a sampling period equal to 1s.

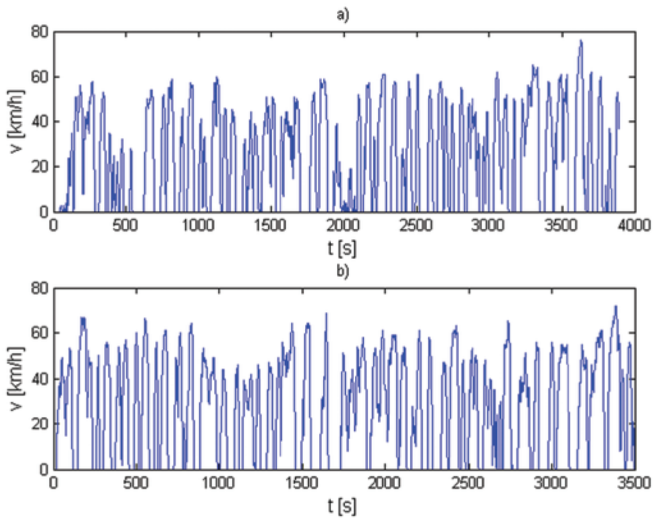

Fig. 5. Examples of vehicle speed change patterns

Multifractal spectra shown in Fig.6 - Fig.7 reflect the decomposition of the actual vehicle speed time series with reference to the abundance of fragments with a specific dynamics of variation.

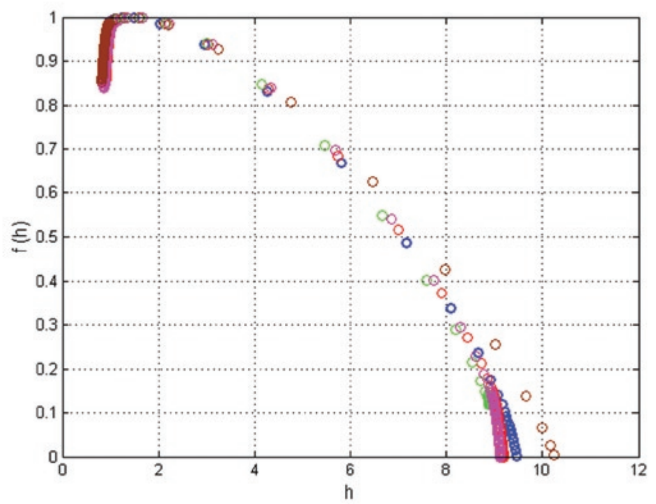

Fig. 6. Multifractal spectra of vehicle speed signals when driving from point A to B

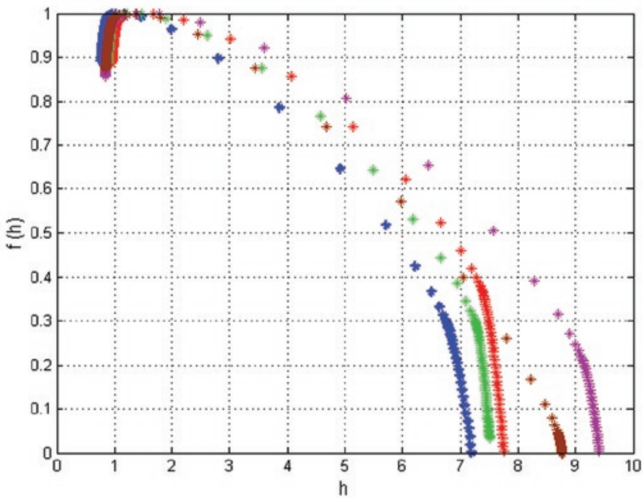

Fig. 7. Multifractal spectra of vehicle speed signals when driving from point B to A

All spectra have similar properties with regard to driving along the same route over consecutive five working days. They exhibit similar values of multifractality levels, singularities with the largest dimension and dimensional range of singularity subsets.

The segments of recorded speed signals exhibiting the largest fluctuations reach dimensions $f(h) > 0.8$. The lowest occurrence probability is shown by the regularity periods described by the singularity exponent $h > 7$. The multifractality level, Δ depending on the day of the week, reaches values in the range from 7 to 9.

5. Conclusions

The conducted analysis confirmed the multifractal nature of vehicle speed fluctuations both within WLTC driving cycle of the universal harmonised test procedure for light vehicles as well as real road conditions of urban driving along the measurement route, being subject of experimental research in Warsaw. Multifractal spectra are characterised by a similar shape and similar values of the level of multifractality. The asymmetric course of the spectra indicates the analogous properties for multifractals obtained as a result of the implementation of the generalised process of the binomial multiplicative cascade [2]. The obtained results indicate the possibility of using the multiplicative cascade process for the synthesis of real operating conditions and short-term forecasting of traffic conditions, which is a critical aspect in the development of intelligent transport systems. This step requires further research including driving in conditions outside urban centres and on motorways.

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