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Application of Fractal Dimension for Estimation of the Type of Passenger Car Driver

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1. Introduction

Chaos theory can be used for quantitative dynamics of uncertainty and finding order in its perturbances. Chaos theory is largely a colloquial notion and is referred to as an analysis of non-linear dynamical systems. The studies devoted to linear dynamical systems and theories of complexity involve studies of turbulence, or, more precisely, the transfer from stability to turbulence. The dynamical system by its nature does not follow long-term forecasts. There are two reasons for the unpredictability. Dynamical systems involve both feedback and critical levels. To paraphrase, one can say that a dynamical system forms a system of non-linear feedback. The most important properties of the system include: sensitivity to the change of the initial conditions, occurrence of critical points and a fractal dimension. Non-linear dynamical systems tend to have more than one solution. The case often is that the number of solutions is huge or even infinite. A visual representation of the data forms a finite space called the phase space of the system. The number of dimensions in the space is determined by the number of variable presents in the system. If there are two or three variables, it is possible to visually examine the data. In case of a larger number of dimensions, the data are examined with the use of mathematical data. Another term used in non-linear dynamical systems is the attractor. This is an area of a equilibrium of non-linear system within a time series. A system which aims to achieve an equilibrium in the form of a single value has a point attractor. Besides, there are phase attractors, which form periodic cycles or orbits in space forming a limit cycle. An attractor, in which none of the points in the space overlaps and whose orbits do not cross but both originate in the same area of phase space, is called strange attractor. Such attractors in contrast to point attractors are non-periodic and predominantly have a fractal dimension [10,11].

2. Fractal dimension in a time series

The fractal dimension forms an important piece of information regarding the system. This is the number which quantitatively describes the way in which an object occupies the

surrounding space. The lowest total number higher than the fractal dimension informs of the minimum number of dynamic variables needed for the development of a dynamic model for a system. Concurrently, fractal dimension determines the lowest number of the possible degrees of freedom. The practical measure used to determine fractal dimension is with the aid of the method developed by Grassberger and Procaccio in 1983 [5]. It involves the determination of a correlation dimension, which forms an approximation of a fractal dimension using correlation integral C(R). This integral determines the probability of finding a pair of points in attractor whose distance from each other is R. The correlation integral is calculated from the following formula

$$C(R) = \frac{1}{N} \cdot \sum_{\substack{i,j=1 \\ i \neq j}}^{N} H\left(R - \left|x_i - x_j\right|\right)$$

where:

$$H(x) = 1 \quad dla \quad R - \left|x_i - x_j\right| \geq 0,$$
$$H(x) = 0 \quad dla \quad R - \left|x_i - x_j\right| < 0,$$

N – number of measurement points,
R – distance.
H(x) takes the form of the Heaviside step function, which assumes the value of 1, when the distance between x_i and x_j is lower than R or 0 when the distance is larger. The correlation integral expresses the probability that randomly selected points are within the distance of less than R units. Along with an increase of the value of R, C(R) should increase at the rate of R^D, where D is the fractal dimension. This hence gives the following relations:

$$C(R) \sim R^D$$
$$\log\left(C(R)\right) = D \log\left(R\right) + const$$

For a given capacity dimension we calculate C(R) by increasing the value of R and setting the inclination of the function log(C(R)) relative to log(R). With the use of linear regression we can determine correlation dimension *D*. Along with an increase of the dimensions of embedding space d, the correlation dimension *D* will approach its actual value. Prior to the calculation of the correlation integral for a time series it is necessary to process the data in order to reconstruct the phase space and in particular in order to determine the capacity dimension and delay [12].

3. Reconstruction of phase space for a time series for a defined capacity dimension and time delay

The object of non-linear analysis is to establish an appropriate state for a given signal s(t) and, in particular, the reconstruction of the dynamic state of the system. In the classical approach the co-ordinates of a state space include displacement and speed. However, in practice it is very difficult to measure them in addition to the lack of information regarding

the original state space dimensions. The up-to-date methods of signal analysis based on the theory of deterministic chaos render it possible to reconstruct the state space equivalent to the original without the necessity of a reference to the derivatives (speed) and dimensions of the original space. It involves the embedding of a time series with the aid of the method of time delay embedding. The procedure involves the identification of a space which is formally equivalent to the original space of the system state, while the identification applies the co-ordinates developed from the observed variables and their delays. The specific duration of the delay time τ can be found as the first occurrence of the zero point crossing of the autocorrelation function for a K(τ) signal. The selection of an appropriate delay time τ has an important impact on the entire dynamic process. The selection of an insufficient value of τ results in an insufficiently short duration of the evolution process for the exploration of the entire state space. The reconstructed attractor will be focused along the main diagonal or along the identical line of the embedded space. The selection of a limited value can lead to the distribution of co-ordinates so far away that they will no longer be correlated. As a result of the internal instability of chaotic system the extended delay time, the relation between the measurement of s(n) and s(n+T) will be equivalent to a random process [1,4,8]. The autocorrelation function can take the form

$$K(\tau) = \sum \left[S_n - \bar{S} \right] \left[S_{n+T} - \bar{S} \right],$$

$$where \quad \bar{S} = \frac{1}{N} \sum_{n=1}^{N} S_n$$

Given a delay time τ the dimension of a state space is estimated, in which the dynamic state is reproduced. For this purpose the dynamic state is reproduced in the subsequent state spaces with gradually increasing dimension with the aid of the false nearest neighbor method. The final number of dimensions is determined by an answer to the question regarding the time when the geometric structure generated within the subsequent two-, three- and more dimensional will be unfolded; that is, when the closeness of the points will come as a result of only dynamic state z not mapping in the space with a smaller dimension. The smallest dimension, which unfolds the attractor, due to which the overlapping is discontinued is called the global dimension of embedding d_G. Every measurement signal constitutes a different combination of original dynamic variables and is capable of generating various global mappings of the original space on the reconstructed space in the d_G dimension. Moreover, d_G is a global dimension and can differ from the local dimensions for a given dynamic state. In order to identify the adequate dimension one can refer to the false nearest neighbor method, which reflects the unfolding of an attractor. It is necessary to take into consideration the following dimensions d=1,2,3,.., and check the successive data vectors and their neighbors for whether the closeness comes as a consequence of mapping or maybe is due to the dynamic characteristics of the system. The neighboring points, which turn out to be the result of mapping are denoted with the term false neighbors. Whether a neighbor is false can be checked by evolution and observation whether the distance between the vectors increases, remains constant or decreases. Given an appropriate dimension and delay time it is possible to develop vectors to reconstruct the dimension of a state space and

its dynamic characteristics. The further course of action may involve an analysis of a trajectory and testing the value of the fractal dimension.

4. Road test

An issue, which has attracted a lot of attention recently, is associated with the modeling of the driver's characteristics. The complexity of driver's behavior and a large number of external parameters affecting it are the major causes why the extensive use of the driver's model can be forecasted as a distant target. Hence the issue of modeling is often limited to a selected aspect of the model, which accounts for the most important characteristics, e.g. style of driving. An appropriate analysis of signals, which reflect the driver's intention, offers the possibility of identification of driver type and interpretation of the driver's behaviors in various situations on the road. On the basis of this information the control system will be capable of selecting an optimum control algorithm and parameters of the engine and powertrain thus adapting to the behavior and expectations of the driver [2,3,6,7].

This paper contains a proposal of the application of non-linear analysis of signal generated on the accelerator pedal by the drive. The classification of the driving style is based on the Grassberger-Procaccio correlation dimension [5].

The test object was the middle class car with a 1.6 dm³ engine and a manual transmission. An optical Datron LS3 sensor has been installed in the car for the measurement of kinematic parameters with a contact free method. The measurement range of the sensor is (0.5÷400) km/h, by generating around 400 impulses per second. Beside the speed and distance the following parameters wee also taken: instantaneous displacement of acceleration pedal and longitudinal acceleration of the car. Data received from the Daqbook measuring interface were subsequently processed with the use of a PC under the supervision of the operator in the passenger seat. This system was used for the registration of the measured parameters with the frequency of 33 per second. Experimental studies involved 76 road tests with the car under various conditions specific to urban traffic, with the length of the road stretch of around 7 kilometers. Selected drivers covered the distance two times, trying to cover the distance in a style which were considerably different in each attempt. Each of the drives was subsequently classified as mild or active. In order to secure a similarity of the measurement conditions the distance was covered at a time of the day when the traffic was the smallest. Fig. 1 illustrates the curves representing the speed of the displacement of the accelerator pedal during car acceleration. The interpretation of the curves indicates that the driver preferring active driving test tend to press the pedal deeper and more intensively in comparison to drivers whose driving style is named mild.

An initial assessment of the results makes it possible to assume with a high degree of probability that it is possible to assess driving style on the basis of the realized speed profile as well as on the basis of analysis of a signal generated by the driver over the accelerator pedal. From the point of view of the control theory this value plays the role of an input signal for the dynamic object, i.e. the car, whereas the speed and car acceleration represent variables of the state and are correlated with this input value. Fig. 2 contains curves representing the changes in the displacement of the accelerator pedal in the function of the speed of the displacement. The presented curves for an active driver display the highest extent of changes both regarding the displacement and speed of the speed of accelerator pedal displacement.
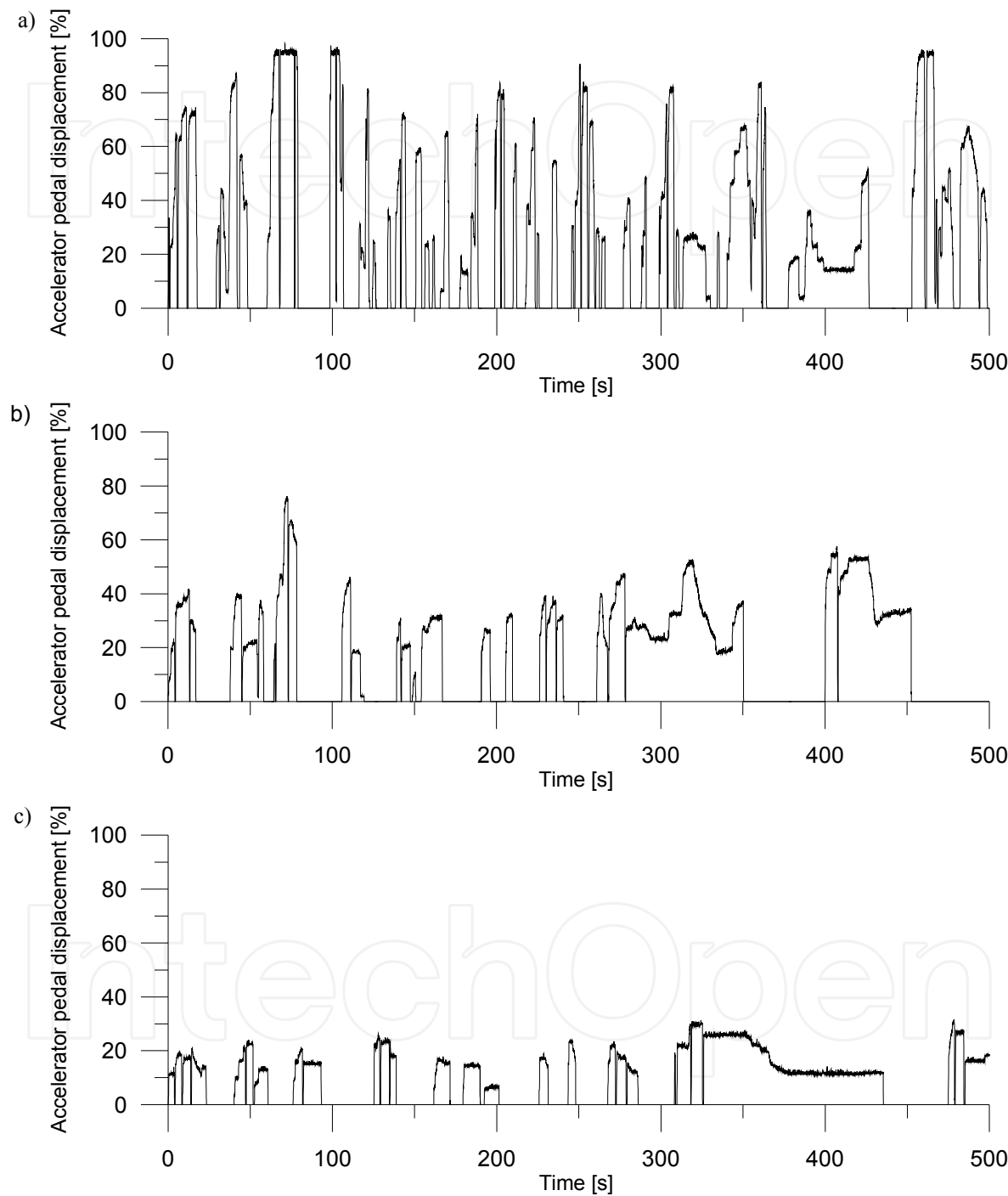
Fig. 1. Displacement of accelerator pedal for the case of a) „active", b) „neutral" and c) „mild" driver.
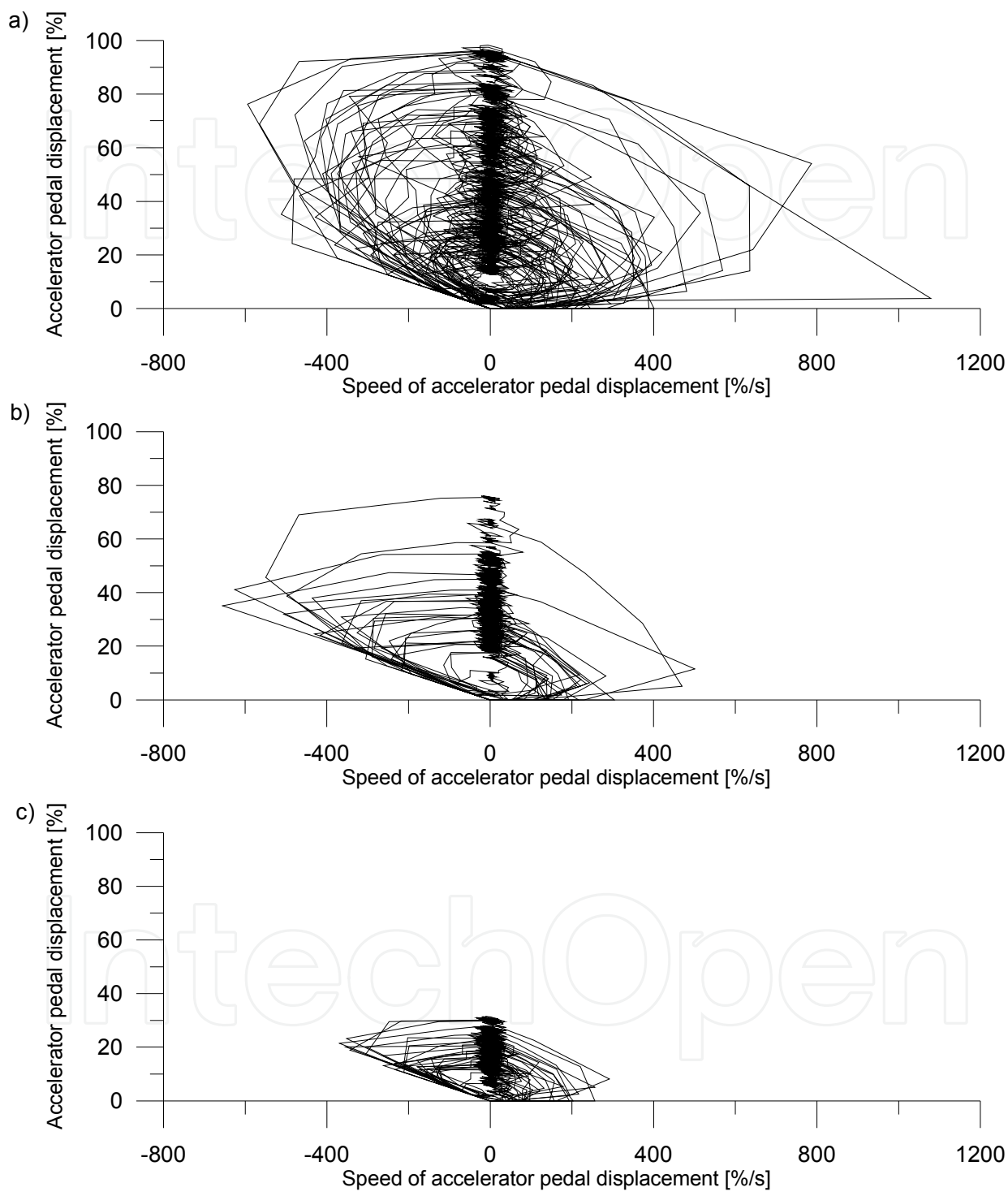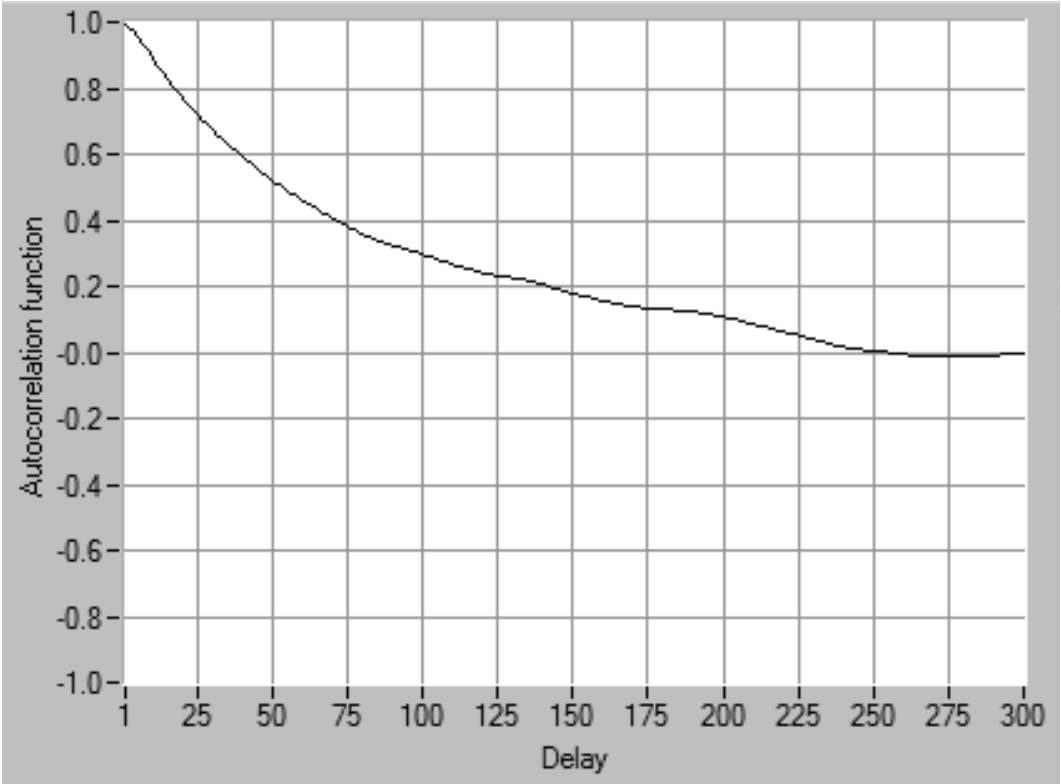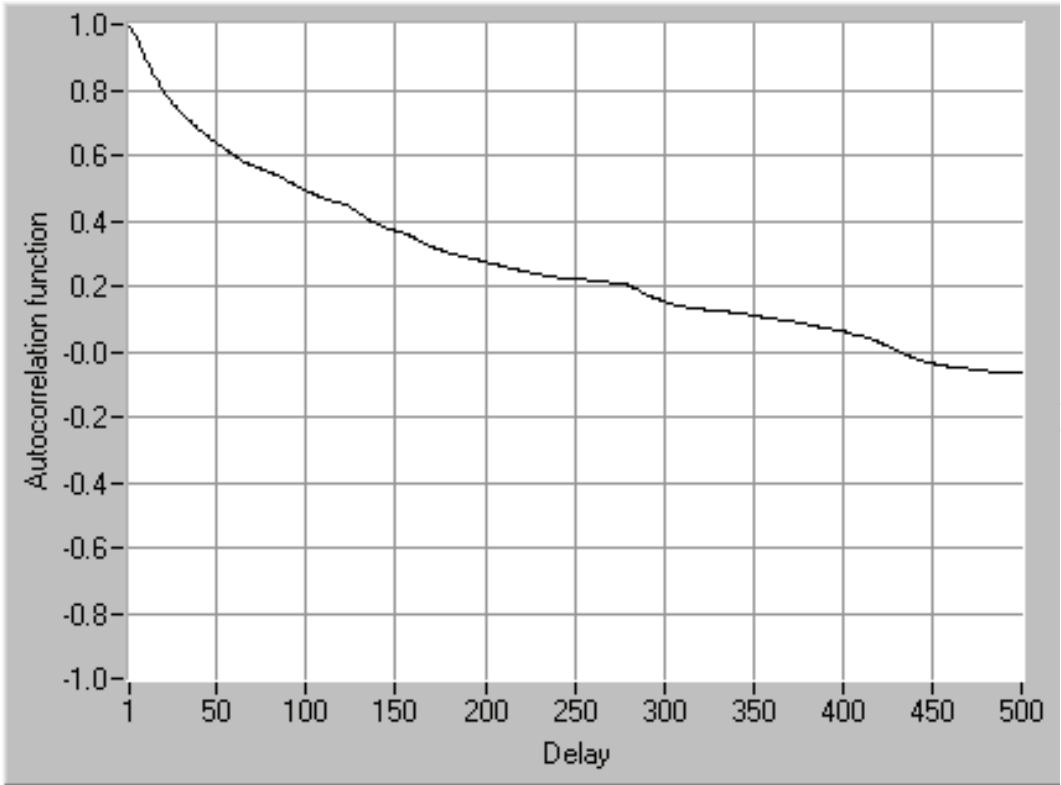
Fig. 2. Speed of accelerator pedal displacement in the function of changes in its speed for the case of a) „active", b) „neutral" and c) „mild" driver

a)

b)

Fig. 3. Delays determined from time histories of autocorrelation function K(τ)
a) active driver τ = 255, b) mild driver τ = 432

5. Correlation dimension of accelerator pedal signal

The signals recorded during road test (measurements of accelerator pedal displacement) were subjected to non-linear analysis with the aim of determination of the correlation dimension with the use of NDT (Nonlinear Dynamics Toolbox) software [9] available online. The object of the testing was the search for a method of estimation of the driver type on the basis of an assumption that it is possible to apply correlation dimension as the estimator of the driver type. In order to do this, time curves of signals generated by accelerator pedal by the drivers were subjected to non-linear analysis. By reference to the results in a rank list presented in paper [2], in which drivers classified from the least to the most active, the relation between the driver type and correlation dimension was established. In the former part of this paper it was indicated that in order for the calculation of correlation dimension t was necessary to determine the values of the delay time τ and dimensions of the embedded space d. The two data formed an input for further calculations. The delay time τ was calculated as the first zero crossing in the history of autocorrelation function $K(\tau)$.The correspondence between driver type and delay τ was not found. Fig. 3 presents the zero crossing places for two types of drivers.

At the same time the embedding dimension d was determined with the use of the false nearest neighbor method. For this purpose an analysis of the charts presenting the relations between dimension d and per cent of false neighbors was undertaken. The charts tend to be monotonically decreasing and did not pose any problems during calculations. The embedding dimension was assumed to be the value of d at which the per cent of the false friends reached zero. It can be concluded that the value of zero was gained for considerably distinct values of embedding dimension d. In the case of this parameter the correspondence between the type of driver was found to be irrelevant. Fig. 4 presents the dimensions of embedding space d for two extreme driver types.

In summary, it was concluded that for all examined signals from the accelerator pedal based on 76 drivers the values of τ and d were diverse. The delay time τ was in the range between 146÷1171, whereas embedding dimension d between 7÷20. The above results were used for the calculations of correlation dimension. The chart representing the relation between $\log(C(R))$ and $\log(R)$ displays a characteristic slope. Only the linear section of the chart was used for the assessment of the correlation dimension D. This results from D being the coefficient of the sloping in this section. The correlation dimensions gained for 76 drivers were grouped into 3 sets. They are presented in Table 1.

Correlation dimension	Number of drivers	Driver types
2<D	4 (5.3%)	„most active" group
1≤D≤2	66 (86.8%)	remaining group
D<1	6 (7.9%)	„mildest" group

Table 1. Results of calculated correlation dimension

The charts with the relations between function $\log(C(R))$ and $\log(R)$ for various driver types are illustrated in Figs. 5, 6 and 7.

In conclusion of the conducted analysis, it can be stated that the proposed chaotic estimator in the form of correlative Grassberger-Procaccio based on the analysis of the signal generated by the driver with the accelerator pedal makes it possible to identify the driver's style. The disadvantage of this method is that it is capable of identifying only the extreme driving types, and hence does not offer graded classification of intermediate types of drivers.
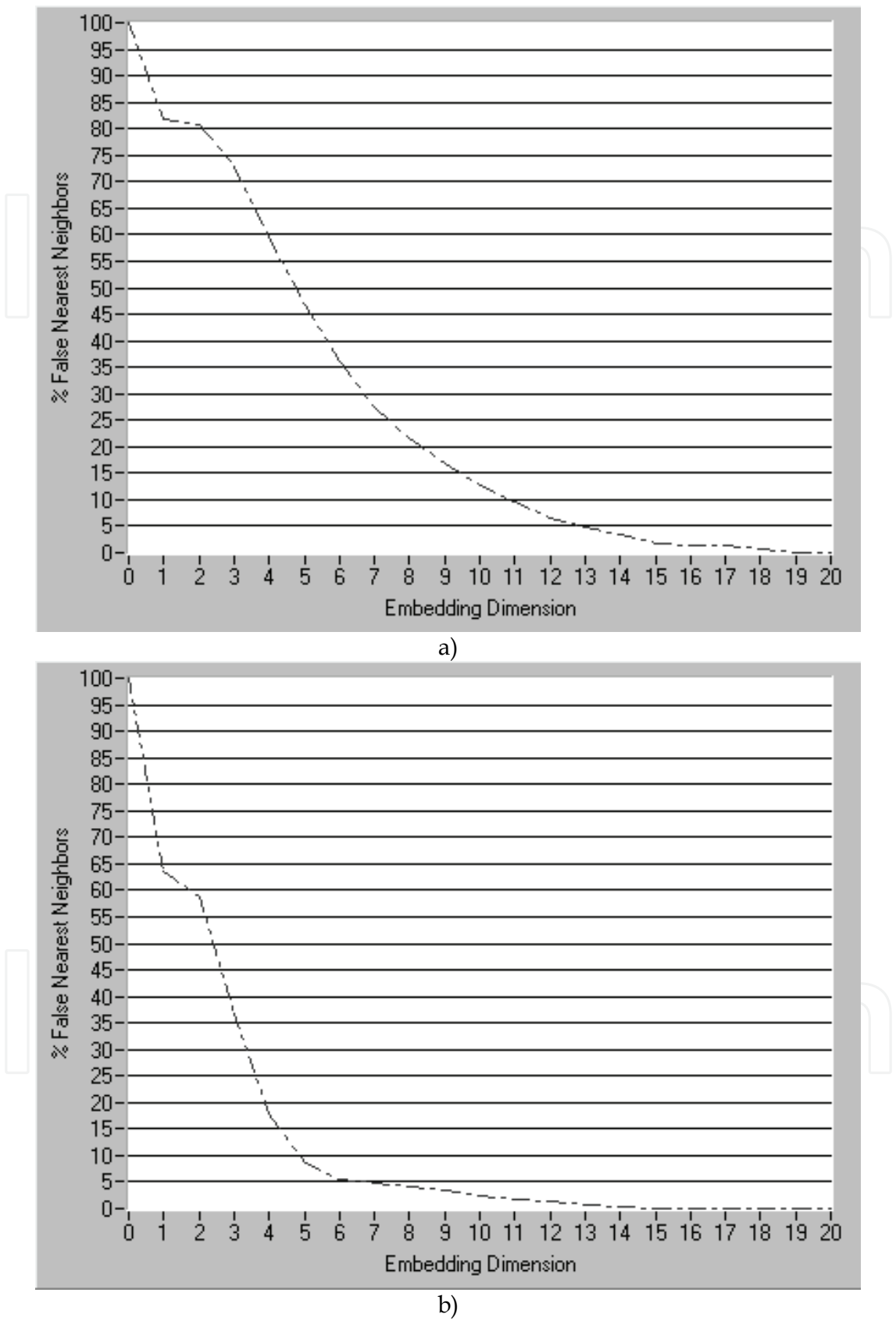
a)

b)

Fig. 4. Embedding dimensions d determined with false nearest neighbor
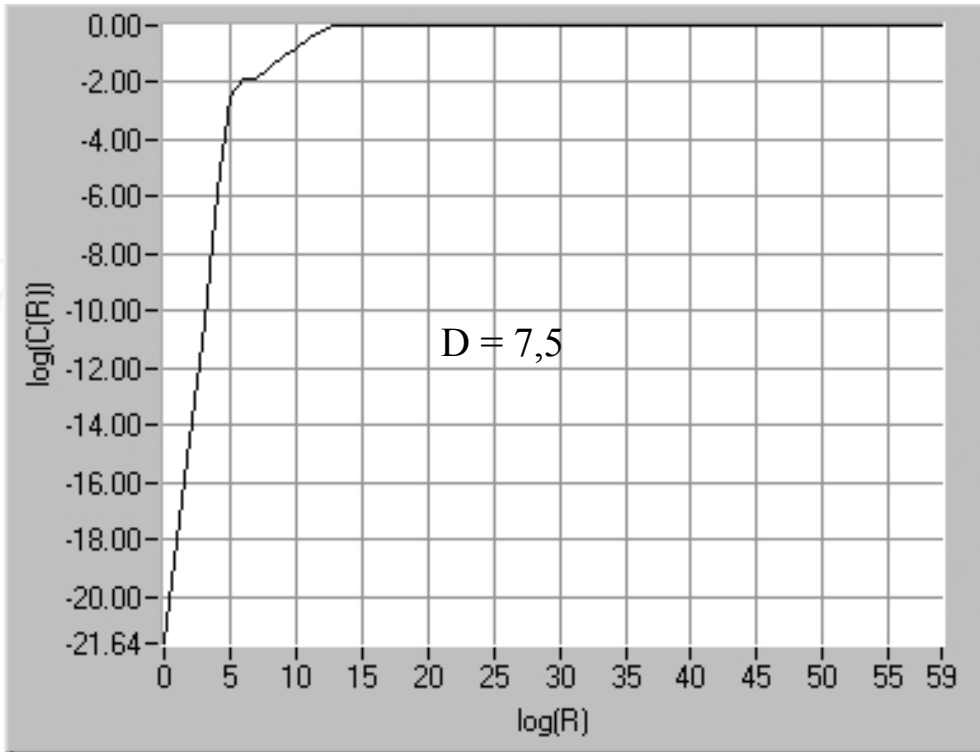a) for an active driver d = 19, b) for a mild driver d = 15

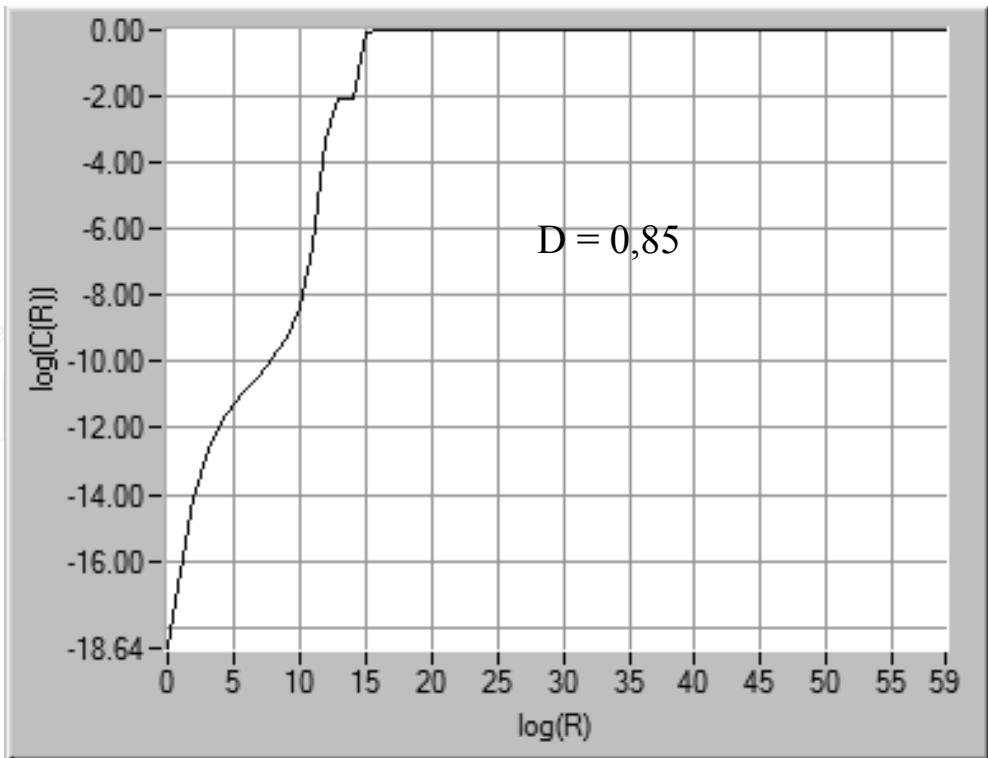Fig. 5. Relation between function log(C(R)) and log(R) for active driver type

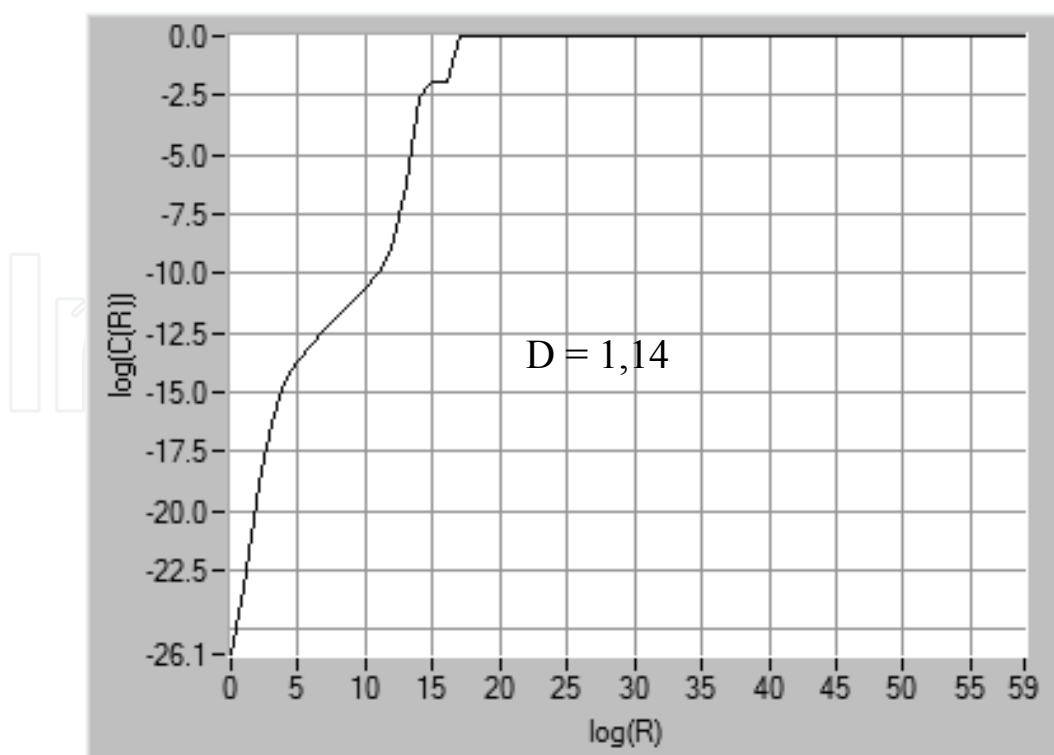Fig. 6. Relation between function log(C(R)) and log(R) for mild driver type

Fig. 7. Relation between function log(C(R)) and log(R) for neutral driver type

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