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Applications of Recurrence Plots in Road Traffic Analysis

Tomasz Grabowski [1] and Maciej J. Ogorzałek [1, 2]

1 *Departament of Elrectrical Engineering, AGH University of Science and Technology, Krakow, Poland*
al. Mickiewicza 30, 30-059 Kraków, Poland
2 *Department of Information Technologies, Jagiellonian University, Krakow, Poland*
Ul. Reymonta 4, 30-059 Kraków, Poland
Email: tomasz.grabowski@poczta.fm , maciej.ogorzalek@uj.edu.pl

Abstract.

Monitoring of road traffic has been studied for many years. This is because of paramount importance of safety, economy, administration, trade and a lot of another issues. One of the road traffic analysis methods is the online identification – so-called Weight-In-Motion (WIM). Classical application of this method for calculation of selected parameters of cars-in-motion, does not give very interesting results for road traffic flow. We propose to use the recurrence plots method (RP) and recurrence quantification analysis (RQA) tool support which permit deeper insight into the properties of the flow. For the analysis we consider measured time series – electric responses of system to moving vehicles stream. We find several characteristic features of the road traffic and also compare them with properties of selected features found in web and phone intensity traffic.

1. Introduction.

This paper deals with the problem of analysis of road traffic parameters based on measurements. Increasing number of vehicles on the roads world-wide has motivated development of electronic sensing techniques for measuring and analyzing traffic conditions. Huge amount of data are gathered using these techniques. Analysis of these data is not a trivial task. Several methods have been proposed in recent years. Statistical methods rely on analysis of probabilities and the underlying mathematical formula (pattern) is in most cases not known and it may be difficult to understand. Another approach proposed is so-called direct method which relies on a system for counting vehicles and measuring their specific features, such as: velocity, length, total weight, number of axes. Implementation of such a system includes inductive loops and piezoelectric sensors placed under the road surface. Since sometimes results of measurements are not easy to understand visualization methods should be introduced. This article presents a discussion concerning description of the road traffic by the recurrence plots method. Based on time series measured using standard equipment installed on the roads near Cracow we constructed various representations of the measured signals and respective recurrence plots revealing specific patterns and properties.

2. Road Traffic Measurements.

As the number of road vehicles has rapidly increased in Poland in the last few years, estimation of road traffic parameters (e.g. traffic flow rate, time intervals between vehicles, travel times) as well as prediction, recognition and classification of cars becomes essential. One of interesting methods of identification of traffic parameters is so-called Identification (Weighting) In Motion (WIM).
The WIM system consists of a group of sensors mounted on the road and a computing system. When a car runs onto detectors electric signals are generated. They are collected and processed by the computing system. In this way we generate the time series which will be used for construction of Recurrence Plots.
In the figure below typical location of detectors on the road is shown. This kind of setup is mounted eg. on the international road E-40 near Cracow. The measurement system includes 5 inductive loops (with different width: 0,1 m – 1,5 m) and 2 piezoelectric sensors. From the first group of sensors we obtain magnetic profiles of cars. The second group delivers supplementary information of specific cars features, such as: velocity, number of axles, total weight and others. Signals derived from them will be discussed in this paper.

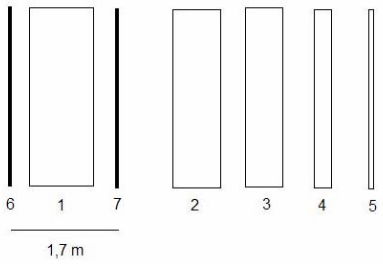


Figure 1. Real measurement set-up
1 – 5: inductive loop sensors (suitably wide: 1,5 m; 1 m; 0,5 m; 0,3 m; 0,1 m), **6 – 7:** piezoelectric sensors (1,7 meters away)

Road traffic analysis is based on detection of vehicles in motion. This process concentrates either on behavior of each vehicle separately, or a stream of cars.
There are two ways of the road traffic analysis:

a) Frequency of passing vehicles measurement
b) Measurement of time interval between two successive vehicles

An electric signal corresponding to a car crossing a particular detector, is registered in the system as a set of samples.

3. Recurrence Plot.

Natural processes can have a distinct recurrent behavior which can be periodic or irregular. The recurrence of states, understood as the states coming arbitrary close after some time, is a fundamental feature of deterministic dynamical systems. This property has been known in nature for a long time and was introduced by Poincaré in 1890.
The Recurrence Plots (RP) method was suggested in 1987 by J.-P. Eckmann to visualize the recurrences of dynamical systems [2]. This tool is giving us the possibility of the visualization of multidimensional dynamics in the new two-dimensional space. Additional tools (e.g. RQA[1]) allow precise analysis of the structure of the plot. There are several definitions of recurrence plots (RPs) referring to their structure and methods for constructing plots (Contact Map, Dots Plot, Similarity Matrix), in most cases we use the first, most prevailing definition following Eckmann:

$$R_{i,j} = \Theta\left(r(i) - \left\|x(i) - x(j)\right\|\right) \qquad (1)$$

where: i, j = 1,2, … , N; r(i) – size of the neighborhood; ||.|| – norm, predefined metric (e.g.: Euclidean, maximal, etc.); $\Theta(.)$ – Heaviside function

$$\Theta(x) = \begin{cases} 0 & for \quad x < 0 \\ 1 & for \quad x \geq 0 \end{cases} \qquad (2)$$

The RP is obtained by plotting the recurrence $N \times N$ matrix (based on equation (1)). The values *one* and *zero* in this matrix can be simply visualized by the colors black and white, using different colors for its binary entries, e.g.,plotting a black dot at the coordinates *(i, j)*, if R*i,j* ≡ 1, and a white dot, if R*i,j* ≡ 0. Both axes of the RP are time axes.

4. Car-stream signal analysis.

An elementary way of analysis of car-streams is continuous measurement of signal for many cars passing over the sensors. In this way we can analyze the intensity and specific properties of road traffic. The time series are generated in time unit by the WIM system. One can consider time intervals ranging from minutes to days or even months. The following conditions can influence the results of analysis:

- Location of the road
- Time measurement of signal
- Date of measurement (holidays, Christmas, Easter, weekend, etc., or weekday)
- Calibration of measurement system d
- Environmental factors
- Repairs of road under consideration
- Repairs of another roads

Essentially we have 2 means for analysis of frequency and the type of road traffic:

a) measurement of magnetic profiles.
b) measurement of electric length of cars.

As one can notice on Figure 2, the majority of vehicles which were moving on the considered road were small cars. The second clearly appearing group was composed of big lorries. In the middle of those two dominant groups we can find midium-size cars, delivery trucks and partially buses. The same features can be noticed in the histograms in Fig.2b.

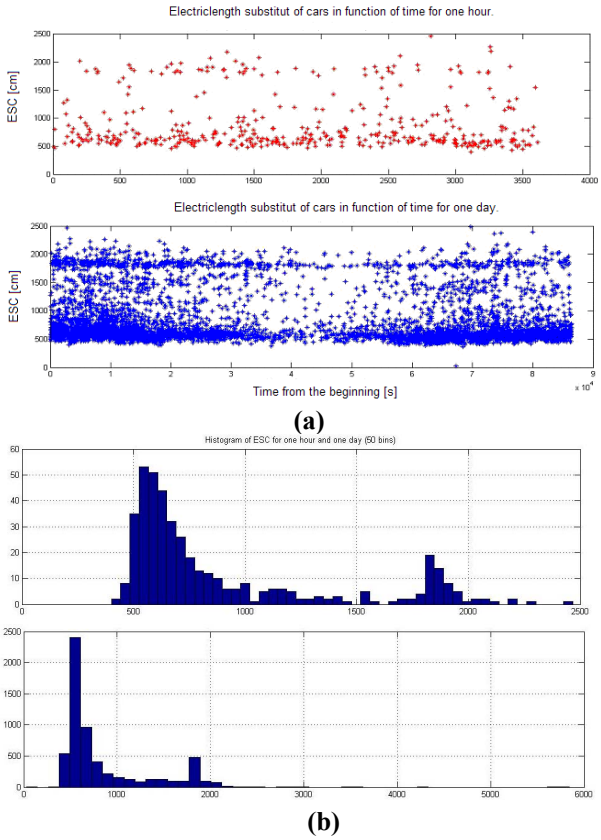
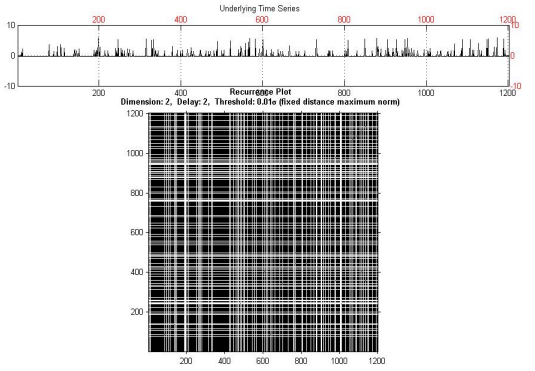


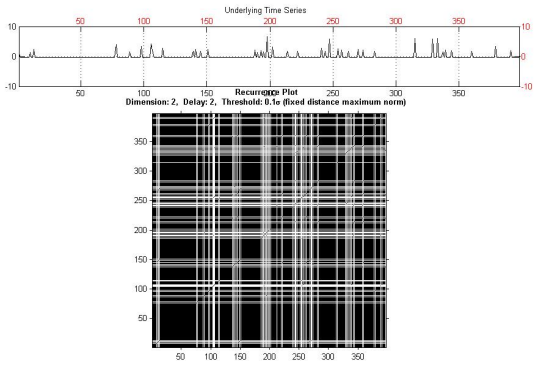
Figure 2. Electric length substitute of cars (ESC) in function of time for one hour and one day (a) as well as histograms for those (b).

[1] A Recurrence Quantification Analysis (RQA), proposed by Webber and Zbilut [9, 10], is a helpful tool for RP plots analysis. It helps to evaluate some characteristic numbers such as: recurrence rate (RR), determinism (DET), laminarity (LAM), divergence (DIV), entropy /Shannon/ (ENTR) and trend (TREND).

On the histograms we notice two, clearly separated groups of vehicles. Another division, namely day and night division is also significant. This situation is noticed *ipso facto* only in the case of daily run. The period of reduced vehicles amount is shown by the central interval in the one day histogram of vehicles activity.
After the introductory and diagnostic analysis, RP for the different lengths of the time series are considered below.



(a)



(b)

Figure 3. Recurrence plot of cars-stream for 20 minutes measurement: all samples (a) and considered 1-400 samples (b).

The white lines correspond to separate cars. Thus a large number of such lines gives information about quite large traffic density. The width of line is related to the size of vehicle. The wider the line – the bigger the vehicle.
One can notice also that the traffic intensity of the given vehicle class in the time unit is random. Nevertheless, we have to note that a different situation can also occur. For example in one moment a heavy column of vehicles moves on the road after a compulsory stop (for example during the heat or holidays). Such events are still marginal and in the long term they do not change the obtained results in a significant way.

Another method of measurement of the road traffic is based on magnetic profiles. Time series, derived from an induction loop sensor is shown in Figure 4.

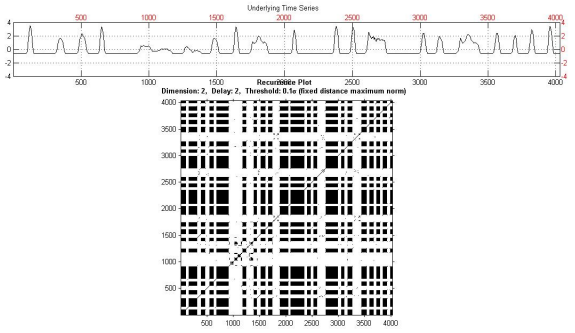


Figure 4. Recurrence plot of stream of 20 different cars passing over an inductive loop.

As can be seen in Figure 4, the structure is neither homogeneous nor periodic or stochastic. The pattern on this plot is atypical. It follows from the structure of time series. Every single vehicle has the different shape, width and height. It is being transferred to the thickness and spread of the lines on the graph.
For examining which cars generate what which shapes of magnetic profiles special time series have been constructed. Structure of the time series, containing 20 identical cars, is visible on the next RP-plot. One can see the periodicity and the image consists of parallel strips of the same breadth.

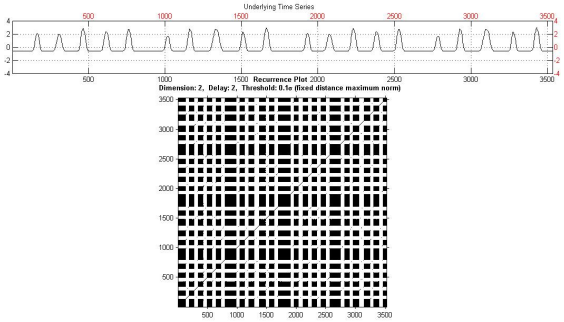


Figure 5. Recurrence plot of a stream of 20 cars. Every 5 cars are separated with the same break.

If we will build the time series from vehicles of different classes (personal, delivery, lorry and buses), then our graph will assume different shapes, of course, the way they showed on the example of the Figures 5 and 6.

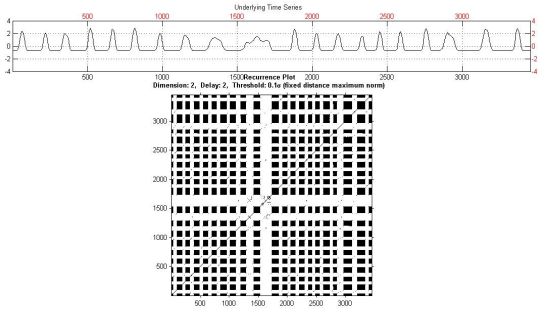


Figure 6. Recurrence plot of stream of 20 different vehicles: cars, delivery-vans and one bus.

When measured series are more and more long, then structures which it is possible to observe on recurrence plots will also be changing. They showed will be more dynamics of the entire stream, rather than single vehicles. Figure 7 shows model built from around 200 personal vehicles.

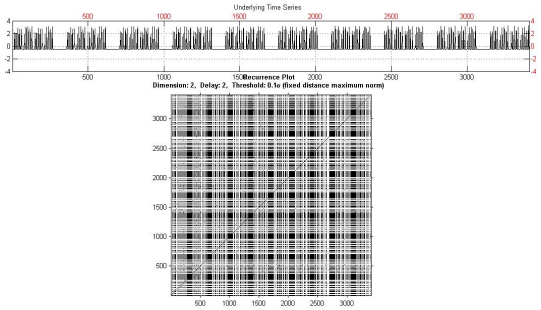


Figure 7. Recurrence plot of stream of 200 personal cars. Every 20 separated vehicles there are the same break of 5000 samples.

When the group of 200 vehicles is divided on 10 identical groups for 20 vehicles and when these groups are separated by identical distance, then we are dealing with the periodicity. We can deal with such a situation in case of heavy traffic on the communications artery, where the cyclical nature of the traffic is a consequence for example of light signals. On the presented plot a length ratio of the break (here: 5000 samples) is essential to the length of the signal describing the vehicle (here: in case of personal cars ca 700 - 800 samples) and lengths of the entire group of 20 vehicles (here: 17680 samples). If the distance between individual groups of vehicles was too small, then the graph would become homogeneous, and distances in a RP-plot would be a unnoticeable. Such situation is shown in Figure 8.

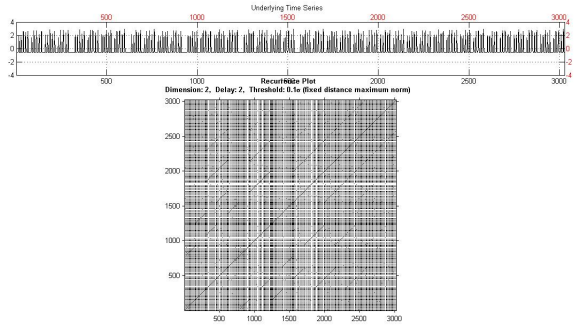


Figure 8. Recurrence plot of stream of 200 personal cars. Every 20 separated vehicles have the same break of 1000 samples of zeroes.

We are not only interested in single vehicles, but also the time intervals between them. This variant, superficially different from previous, is natural fulfillment for its. We can focus one's attention on the intensity of road traffic. Figure 9 shows specificity of this approach.

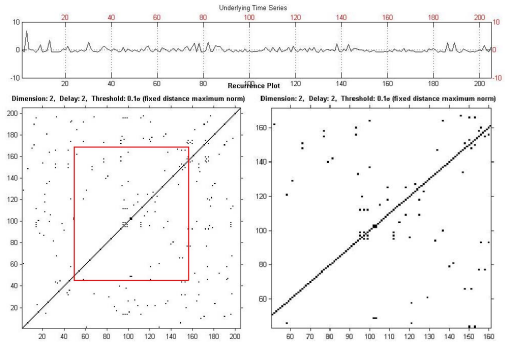


Figure 9. RPs of time intervals between vehicles for the time 30 minutes.

RPs above are characteristic for random time series and stochastic processes [3]. It is necessary to notice, for time 30 minutes there are microstructures on the plot.

5. Conclusions and outlook.

Performed experiments showed, that WIM system delivers a lot of interesting information about road traffic. One can obtain for analysis both data of cars-streams and single vehicles. In contrast to statistic methods RP permits to effectively combine several features for visual inspection and characterization of dynamics of the system. RPs with RQA can be useful for classification of vehicles in motion. Results of interpretations of time series are sometimes difficult, still RPs are interesting aid for analysis cars-stream time series.

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