Analyzing nonlinear time series of multi-lane highway traffic volume

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Abstract. Recent researches have demonstrated chaotic phenomena existing in traffic systems. Much attention was focused on the nonlinear time series technique to analyze the traffic data collected from detectors or from traffic flow models. For real highway systems, it usually consists of two or more lanes. Vehicles on different lanes affect each other, especially for a traffic jam. The purpose of this paper is to analyze nonlinear dynamical behaviours of traffic on different lanes based on 1-minute-interval. Typical time series is checked, traffic characteristics on different lanes are analyzed. It is found that both chaos characteristics and stochastic phenomena appear in the traffic flow.

1. Introduction
Traditionally, traffic flow system may be described in terms of variables such as the rate of traffic flow, density and speed from a macroscopic viewpoint, it considers the temporal evolution of these variables, equilibrium and steady state operations are essential for analyzing, managing and optimizing traffic flow. However, Equilibrium and steady state operations are ideal but not assured as traffic is inherently unstable. Faced with such challenges, nonlinear dynamics theory was used to describe the traffic flow system.

Analyzing nonlinear dynamical behaviors of traffic flow fascinates the interests of many researchers. It is found that traffic flow is chaotic characteristics exist in the traffic system, from traffic flow data with short time interval (1-minute, for example) or day-to-day. Disbro and Frame (1989), Dendrinos (1994) found that nonlinear chaotic phenomena with short-term traffic flow. Van Zuylen et al. (1999) discussed chaos and unpredictability for urban and transportation planning and forecasting with implications of human behaviors. Shang et al. (2005) applied time series techniques to analyze 2 minutes interval speed data of peak hour, and find chaotic characteristics exist in the traffic system. Lan et al. (2005) presented a parsimony procedure with surrogate date to identify the chaotic phenomena in short term traffic flows. Lin and Lan (2005) examined ten days morning commuting hours from 6:00am to 9:00am each day, and measured by different time scales on I-35 freeway in Minneapolis, Minnesota. They found that the traffic data are measured in one minute, the traffic dynamics in the morning hours exhibit chaotic phenomena. However, the chaotic phenomena may disappear if the same data measured in five minutes and ten minutes. Furthermore, Li and Gao (2004) studied the characteristic behaviors of traffic flow with nonlinear time series analysis approach, where
the traffic time scales is obtained from the deterministic NaSch traffic model. Fu et al. (2004) further studied the NaSch traffic model. Xu and Gao (2007) further analyzed the characters of trip distribution in general transportation network, and assumed the path choice satisfy user equilibrium conditions. Li and Shang (2007) analyzed the Multifractal character of road traffic flow.

The objective of this paper is to find the nonlinear dynamical behaviors based on the detector data on highway, which were collected on 4 lanes and 24 hours. We study 1-minute-interval traffic volume time series. The paper is organized as following. In the next section, the nonlinear time series techniques are introduced, which includes phase space reconstruction and maximum Liapunov exponent. Empirical data and analysis are shown in Section 3, including the traffic volume time series on four lanes with three time parts, the statistics properties of chaos and stochastic characters. The paper is summarized in the last section.

2. Techniques for nonlinear time series analysis

The traffic volume data are ordered as a sequence in time, we speak of traffic volume time series. The interpretation of traffic volume time series plays an important role in determining the existence of chaos. Given a time series \(\{x_t\}, t = 1, 2, \ldots, N, \ldots\), for analysis the nonlinear characters, a wide used method is to reconstruct the phase space with delay time method. Suppose the embedding dimension \(m\) and delay time \(\tau\) are given, an “equivalent” phase space can be reconstructed as a time series vector \(Y_t = (x_t, x_{t+\tau}, \ldots, x_{t+(m-1)\tau})\).

Correlation dimension \(d\) and delay time \(\tau\) are two important parameters in the phase space reconstruction. Many researchers mentioned this problem (Takens, 1981), for example, if we make delay time \(\tau\) too small or too big, it can not embody the characters of the system. Grassberger and Procaccia (1983) presented an effective method to decide the correlation. The delay time \(\tau\) approximates with the autocorrelation function method, see Alligood (1996) for details.

With phase space reconstruction method, the distribution of trajectories in the reconstructed phase space can display the characters of the system. When the trajectories converge to a point, it means the system is stable. When the trajectories form a close curve, it means the system will be periodic. If the trajectories scatter uniformly in an area, the system may on stochastic state. Furthermore, if the trajectories have stranger attractor, the system demonstrates chaotic.

Figure 1. Traffic volume time series analysis procedure.

In order to provide the evidences of deterministic chaos in the traffic volume time series, we can calculate the maximum Liapunov exponent (LE) for the \(m\) dimension phase space, which result in \(m\)
different Liapunov exponents. From the chaos theory, if LE is equals to zero, it means the traffic is periodic. If LE is less than 0, the traffic is stable. If LE is great than zero, the traffic can be unstable.

According to the chaos theory, we build a traffic volume time series analysis procedure to test the nonlinear structures of traffic dynamics, as shown in Figure 1.

3. Empirical data and analysis
In this study, the 24 hours real time traffic volume data on a 4-lane highway are used, which are collected from loop detectors. There is a ramp behind the detector place as shown in Figure 2, the distance between which is about 0.11 miles.

From the loop detector, the traffic volume data in a certain time interval can be obtained by counting the number of “1s”. In this study, the volume is collected with 1 minute interval on four lanes. There are 5740(1435*4) volume data in total, from 12:00am to 11:55pm on four lanes. For convenience of comparison, the data was separated into three parts: from 12:00am to 7:58am (Part I, 478 data points), from 7:59am to 3:56pm (Part II, 480 data points) and from 3:57pm to 11:55pm (Part III, 477 data points). The volumes on different time parts and different lanes see Table 1. The travel volume time series on the three time parts on lane 1, lane 2, lane 3 and lane 4 can see figure 3, 4, 5, 6.

From Table 1, the maximum and minimum total traffic volume is on lane 2 and lane 4, the total traffic volume on lane 1 and lane 3 is similar and less than lane 2. Traffic volume on time Part I and III on lane 1 and lane 4 has no bigger difference, however, a clear difference on lane 2 and lane 3. Traffic volume on time Part II has maximum than corresponding traffic volume on Part I and III on all lanes, however, traffic volume on time part II has maximum on lane 2 and minimum on lane 4. From Figures 3-5, the total traffic volume trends on four lanes are similar. On time Part I, traffic volumes on each

Figure 2. Schematic figure of the study site including 1 ramp.

Figure 3. Traffic volume time series on lane 1  Figure 4. Traffic volume time series on lane 2
From Table 1, the maximum and minimum total traffic volume is on lane 2 and lane 4, the total traffic volume on lane 1 and lane 3 is similar and less than lane 2. Traffic volume on time Part I and III on lane 1 and lane 4 has no bigger difference, however, a clear difference on lane 2 and lane 3. Traffic volume on time Part II has maximum than corresponding traffic volume on Part I and III on all lanes, however, traffic volume on time part II has maximum on lane 2 and minimum on lane 4. From Figures 3-5, the total traffic volume trends on four lanes are similar. On time Part I, traffic volumes on each
lane are small and stable then increase rapidly. On time Part II, traffic volumes are large and maybe cause congestion frequently, and on time Part III, the traffic volumes decrease first, then stable again. However, the variation scale on each lane on the same time part is different.

**Figure 5.** Traffic volume time series on lane 3

**Figure 6.** Traffic volume time series on lane 4

**Table 2.** Statistics of Traffic Volume Time Series for Different Time Parts and Lanes

| LANE   | TIME  | A  | B | C    | D     |
|--------|-------|----|---|------|-------|
| Lane1  | Part I| 58 | 7 | 1.1715 | 0.015499 |
|        | Part II| 1 |   | ----- | ------- |
|        | Part III| 15 | 23 | 2.7143 | 0.0093669 |
| Lane2  | Part I| 58 | 7 | 1.4635 | 0.014969 |
|        | Part II| 1 |   | ----- | ------- |
|        | Part III| 31 | 12 | 2.2976 | 0.0011748 |
| Lane3  | Part I| 55 | 7 | 1.502 | 0.010875 |
|        | Part II| 1 |   | ----- | ------- |
|        | Part III| 35 | 11 | 2.4046 | 0.0085829 |
| Lane4  | Part I| 45 | 8 | 1.2628 | 0.0076857 |
|        | Part II| 1 |   | ----- | ------- |
|        | Part III| 21 | 16 | 2.0789 | 0.010992 |

A: Delay time. B: Embedding dimension. C: Correlation dimension. D: Largest Liapunov; Part I: 12:00am--7:58am, Part II: 7:59am--3:56pm, Part III: 3:57pm--11:55pm
Table 1 Traffic Volume on 4 Lanes

| LANE | TIME | VOLUME | TOTAL |
|------|------|--------|-------|
| Lane1 | Part I | 5228 | 21511 |
|      | Part II | 10289 |       |
|      | Part III | 5994 |       |
| Lane2 | Part I | 5801 | 25758 |
|      | Part II | 11982 |       |
|      | Part III | 7975 |       |
| Lane3 | Part I | 4856 | 21981 |
|      | Part II | 10187 |       |
|      | Part III | 6938 |       |
| Lane4 | Part I | 3243 | 13678 |
|      | Part II | 6387 |       |
|      | Part III | 4048 |       |

Part I: 12:00am--7:58am,
Part II: 7:59am--3:56pm,
Part III: 3:57pm--11:55pm

Table 2 demonstrates the statistics indexes for the traffic volume time series on different time parts and lanes, which is based on the analysis procedures given in Figure 1. From Table 2, it is found that chaos exist on time Part I and Part III, however, stochastic phenomena exist on time Part II. Considering the chaos characters exist on the highway on certain time parts; therefore, traffic volume can be forecasted on these two time parts. For traffic volume on time Part II, the traffic demonstrates stochastic characters, it needs new ways to traffic estimation. For the maximum Liapunov exponent on time Part I and on lane 1, lane 2, and lane 3, it is greater than the corresponding value on time Part III, that is to say, the chaos characters on time Part I are more obvious than on time Part I. So, the forecasting is longer on time Part III. For the traffic characters on lane 4, the case is opposite. Therefore, we can forecast longer on time Part I.

4. Concluding Remarks

In this paper, traffic volume time series got from loop detectors are used to analyze the traffic behaviours on different lanes. A numerical analysis procedure is presented to check the traffic characters on different lanes. From the procedure, we check the traffic volume time series on whole 24 hours with 1-minute-interval and separate it into three time parts, which includes the characters of traffic volume on three different intervals. It is found that traffic flow on time Part I and III has chaos characters on 4 lanes. For lane 1, lane 2 and lane 3, the chaos degree on time Part I is more obvious than that of time Part III, however, an opposite case for lane 4. The traffic flow on time Part II demonstrated stochastic characters on all the lanes.

The practical application of this study is important. Traffic flow characters are different on different lanes and on different time parts. For better forecasting traffic flow, which is a base for developing advanced traffic management and information systems of Intelligent Transportation System (ITS) and many other analyses, it can take advantage of the chaos characters to estimate traffic flow; however, traffic flow chaos characters are different on different lanes and time intervals. It also should be noticed that traffic appears stochastic characters on some time parts. Therefore, before estimating...
traffic flow, it needs to make clear the traffic characters, and then chooses the fit methods for different traffic time series.

We only analyze one detector station data with 1-minute-interval for four lanes. For further studies, it needs identify the effects of traffic flow character by multiple detector stations, and also the traffic flow features on different time-scales. How to manage and control the traffic flow based on the different traffic flow characters is also need to consider further.

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