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Using Chaos Theory to Identify the Dynamic States of an Urban Road Network for Traffic Control

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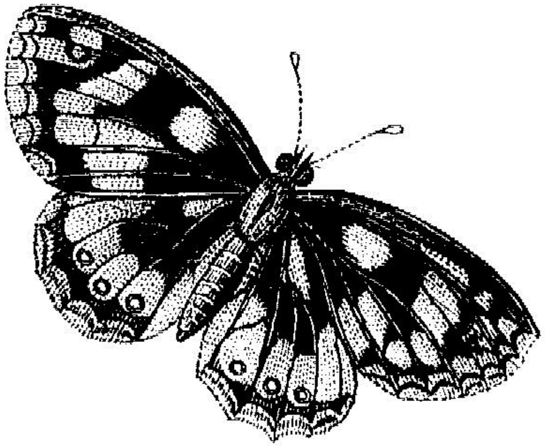
This presentation gives the results of the first stage of my research for a PhD at Newcastle University and therefore it is currently not published. Please treat the content sensitively and contact Abraham Narh (a.t.narh@ncl.ac.uk) for any detailed information.

Outline of Presentation

- Background
- Challenges of UTC
- Chaos Theory
- Lyapunov Exponents
- Examples of Lyapunov Profiles
- Conclusion



The Butterfly-Effect

Phase Portrait

Background

- **Increase in road traffic and travel demand**
  >> congestion, delays, accidents
  >>> detrimental impact on environment

- **Road transport >> 90% of $C0_2$ emissions from the transport sector (DfT, 2004)**

- **89% of delays due to congestion in urban areas.**

- **By 2025 if left unchecked, will cost an extra £22 billion worth of time in England alone (Eddington, 2006)**

- **By 2025, 13% of traffic in congestion will be subject to start-stop conditions (Eddington, 2006)**

Climate Change

Poor Air Quality

Economic Costs

Challenges of UTC

- *UTC Systems e.g. SCOOT*
  - *perform well in under-saturated traffic conditions,*
  - *manage queues on a local level*
  - *Assume 'fixed plans' during over-saturated conditions*
- *Unable to reliably forecast the onset of congestion*
  - *in real-time*
  - *on a local or strategic level*
- *Chaos Theory has potential to help tackle this challenge*
- *Allowing effective preventative action by adjusting in advance traffic signal settings appropriately*

Chaos Theory

Finding the Lag Time (τ)

- *The autocorrelation coefficient at lag τ is given by:*

$$C(\tau) = \frac{\sum_{i=1}^{N-\tau}[x(i) - \bar{x}][x(i+\tau) - \bar{x}]}{\sum_{i=1}^{N}[x(i) - \bar{x}]^2}$$

where:

- $\bar{x}$ **is the mean of observed data series;**
- $x(i)$ **is the preceding time observation;**
- $x(i+\tau)$ **is the observation at the lagged time** (τ)

- ***Plot the autocorrelation coefficient against the lag τ to establish the solution that is independent*** $C(\tau)$ ***=0.4***
- ***For occupancy lag τ was 25-33 minutes for different months of the year***

Finding the Dimension

- *Correlation Dimension/Embedding Dimension:*

Consider two points in the reconstructed phase space:

$$\mathbf{X(j) = x(j), x(j+\tau), x(j+2\tau), \ldots\ldots\ldots\ldots\ldots.. x(j+(m-1)\tau)]}$$

..............................(1)

$$\mathbf{X(i) = x(i), x(i+\tau), x(i+2\tau), \ldots\ldots\ldots\ldots\ldots.. x(i+(m-1)\tau)]}$$

..............................(2)

Let $\mathbf{r_{ij}}$ (m) denote the distance between them, so that:

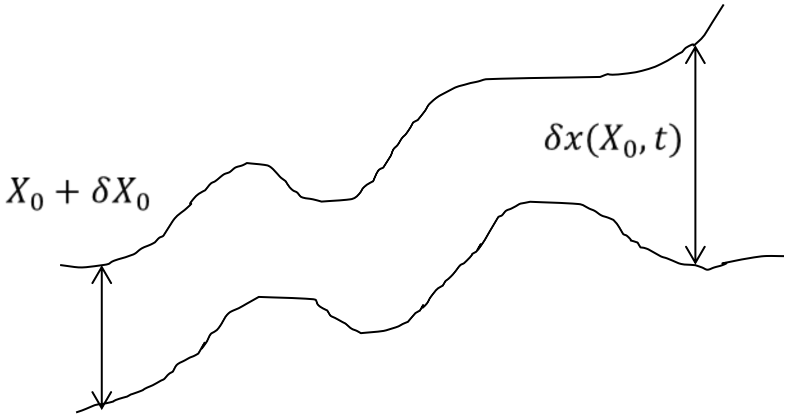
$$\mathbf{r_{ij}(m) = \|X_i - X_j\|}$$

- *For occupancy the dimension was 3*

Lyapunov Exponent

- ***The instantaneous Lyapunov Exponent is given by:***

$$\lambda = \lim_{\substack{t\to\infty \\ |\Delta X_0|\to 0}} \frac{1}{t} \ln \left| \frac{dx(X_0, t)}{dX_0} \right|$$



where:

- **dX_0 is the initial separation betweem two points;**
- **$dx(X_0, t)$ is the separation after a time lapse t**

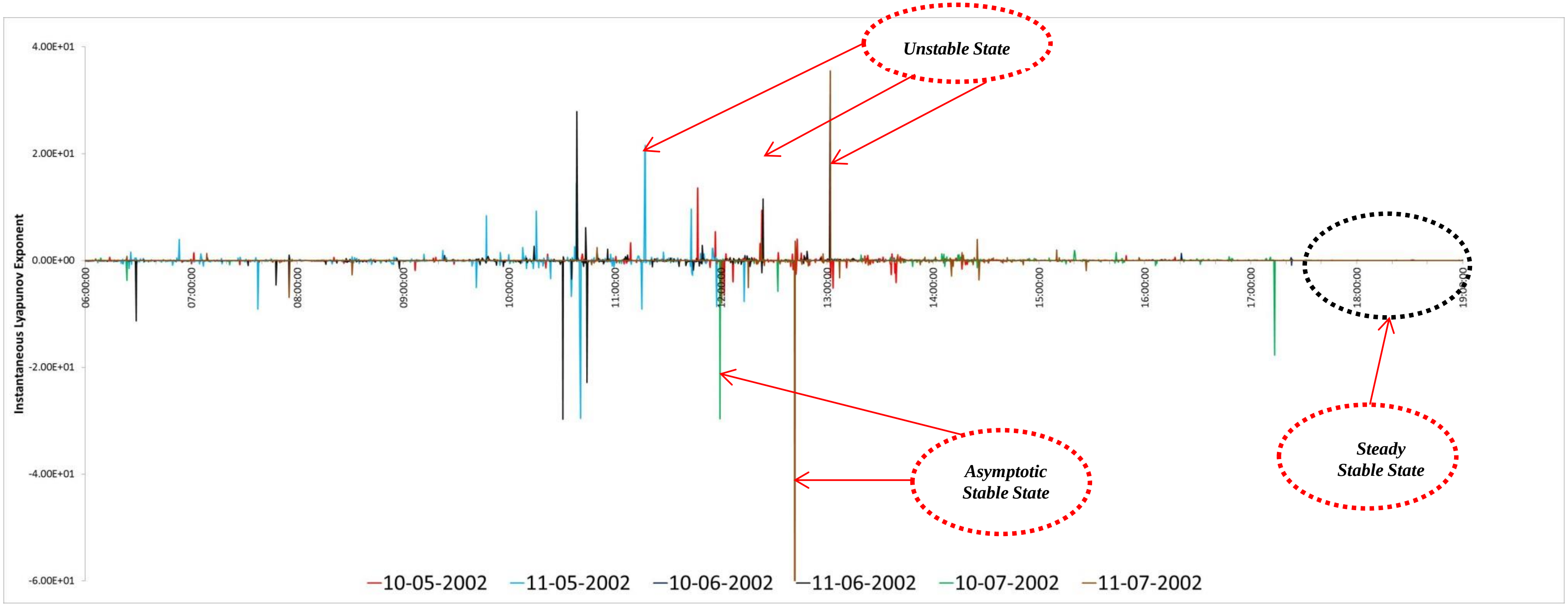
- ***Lyapunov exponent is a measure of congestion performance***

Identifying states of congestion

- ***Requires time series data (e.g. from Motes, Bluetooth, ANPR, SCOOT) to estimate the Lyapunov Exponent***

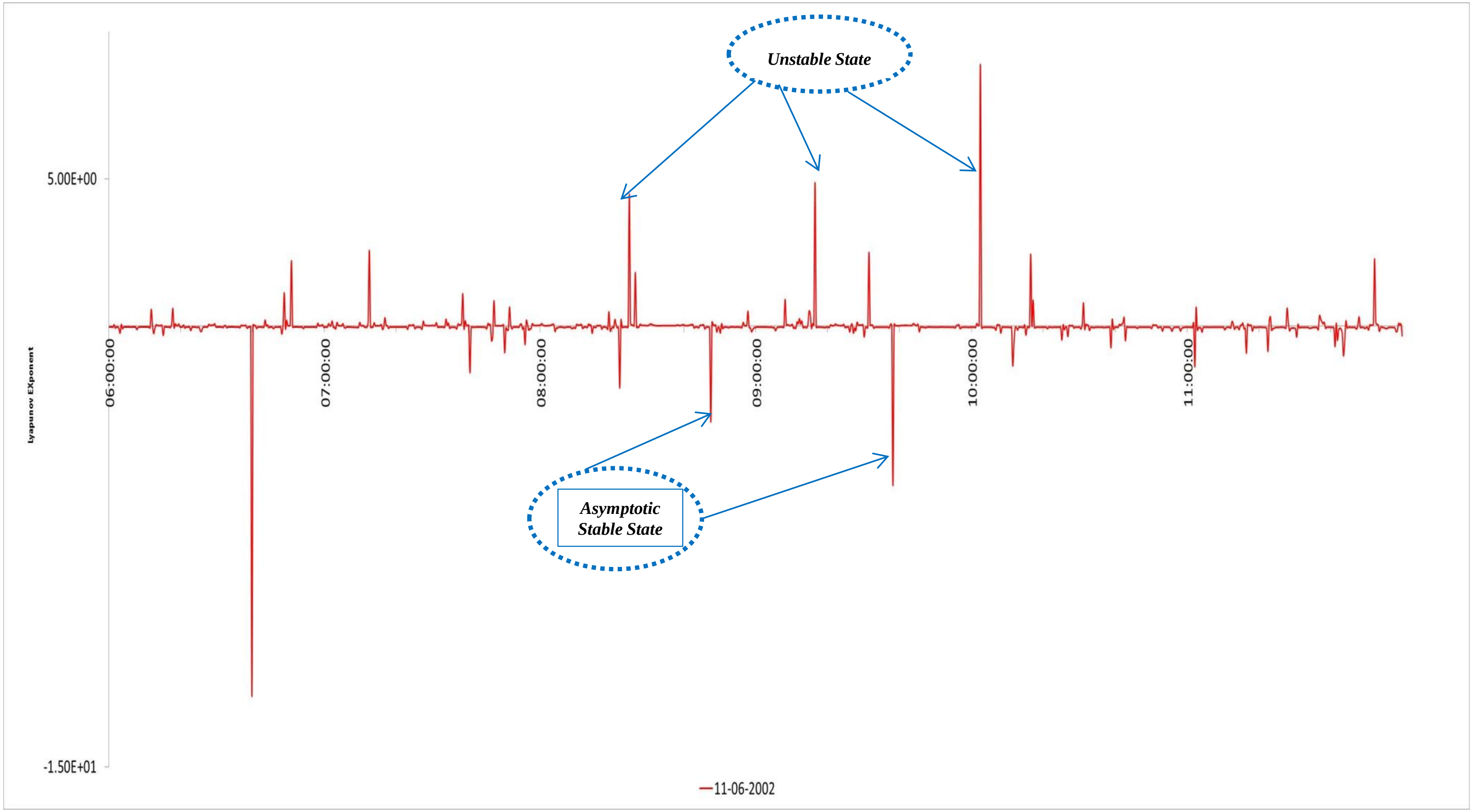
- ***Detect chaotic behaviour using the Lyapunov Exponent (λ):***
  - **If $\lambda < 0$, traffic is asymptotically stable (No congestion);**
  - **If $\lambda = 0$, steady traffic state i.e. exhibits Lyapunov stability;**
  - **If $\lambda > 0$, chaotic traffic state (emergence of congestion)**

Results: Lyapunov Profiles



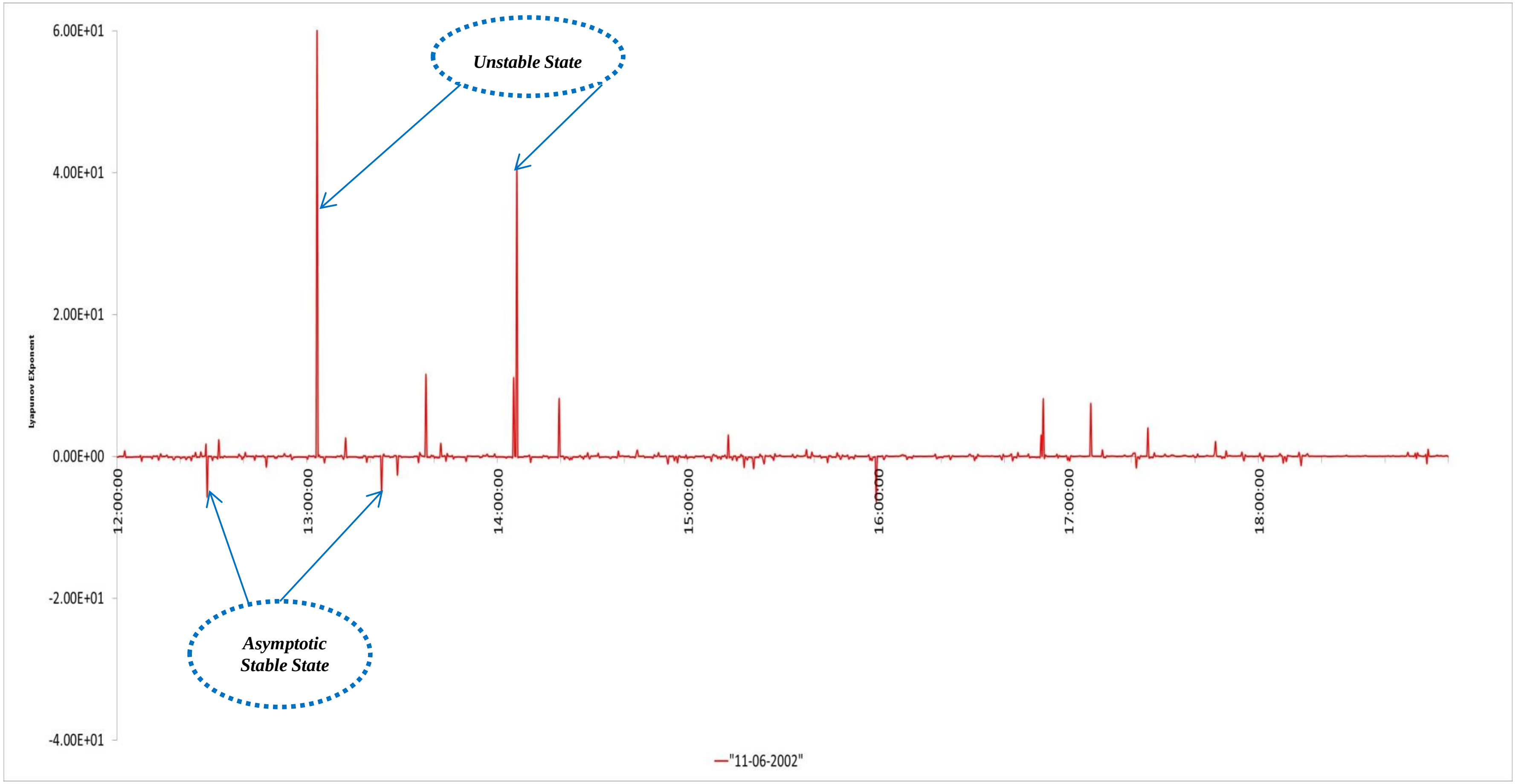
Results: Lyapunov Profiles

- **Lyapunov Profile (from 0600 to 1159, 11-June-2002)**



Results: Lyapunov Profiles

- **Lyapunov Profile (from 1200 to 1859, 11-June-2002)**



Next Step

- ***Developed Lyapunov Exponent as an indicator of the on-set of congestion for a link over time***
- ***Next step is to develop a method to establish relationship between the cause and effect spatially over time across the network***
- ***Data sources that give an area-wide view of the evolution of congestion will enable traffic to be managed to avoid SCOOT junctions becoming over-saturated***

Conclusion

- ***For SCOOT link occupancy at 20 second sampling interval there are slices (lags of 25-33 minutes duration) of time that are independent***
- ***Blocks of 3 slices behave independently***
- ***Lyapunov Exponent can enable traffic managers to forecast the onset of congestion in real-time over the network***
- ***Chaos Theory to enable traffic to be managed to avoid SCOOT junctions becoming over-saturated***

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Thank you for listening

Any Questions?

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