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Identification of country specific characteristics of oscillating congested traffic
Diploma thesis

Identification of country specific characteristics of oscillating congested traffic

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Abstract

This thesis aims at a country specific analysis of freeway traffic oscillations. Toward this end, loop detector data from sites in the USA, Germany and the United Kingdom (UK) was analyzed.

By using a method applied in previous work, traffic oscillations were identified in all three countries. Calculation of the cross-correlation coefficient reveals that they travel upstream at speeds of about 19–20 km/h at the site in the USA, 16 km/h at the German site and 14 km/h on the UK freeway. Similar magnitudes were found in the literature verifying the hypothesis that they propagate faster in the USA than in Germany.

Furthermore, an oscillation frequency was identified by calculation of the data’s autocorrelation. For the sites analyzed, it was found that oscillations appear every 8 – 12 min in the UK, 10 – 30 minutes in Germany and every 3 – 6 minutes in the USA. The magnitudes for the latter two countries are supported by the literature; therefore this indicates that a general difference in the oscillation frequency exists. However, further research on different sites is needed to verify this statement. Since a relation between the frequency and amplitude of traffic oscillations is believed to exist, this would also indicate that the amplitude is usually lower in the USA than in Germany.
Acknowledgements

This is not a usual thesis. Even though officially referring to Dresden University of Technology (TUD), Germany, it was written at and supported by Portland State University (PSU), Department of Civil and Environmental Engineering, USA. I am very grateful that I had the chance to write my thesis abroad. Therefore I would sincerely like to thank Dr. Bertini (PSU) and Prof. Helbing (TUD) for making this happen. They were willing to accept a new approach and made this possible.

No scientific work can be done without feedback, criticism and new ideas. Therefore I was lucky I could work at Portland State University, Department of Civil and Environmental Engineering, since then Prof. Bertini was available for regular discussion. He questioned my approaches and gave me new ideas to continue my work. This is another reason I show my sincere gratitude to him.

Martin Treiber (TUD), Martin Schönhof (TUD) and Soyoung Ahn (Arizona State University) have given me advice and hence contributed to a greater understanding on traffic flow.

I want to thank Marek Junghans (TUD), my previous supervisor. He supported me during my student research project (“Studienarbeit”). In long meetings he strived to give me insights on the scientific approach. He is certainly the person I have learnt from most before coming to Portland and has prepared me well for this research.

No empirical analysis is possible without a good source of data. Therefore I thank Mr. Stuart Beale of the U.K. Highways Agency and Mr. Tim Rees, Transport Research Laboratory, UK, for generously providing the M4 data. The A9 data was provided by Christian Mayr and Dr. Thomas Linder at the Autobahndirektion Südbayern with the support of Dr. Klaus Bogenberger of the BMW Group. I am also grateful to the Oregon Department of Transportation and the PORTAL group, sponsored by the U.S. National Science Foundation, for supplying me with the OR 217 data.

My most personal thanks go to my lab mates for their regular diversion and ping pong games (especially with Nick Carey). They have contributed to make my stay here in Portland a great experience I will never forget.
Hypothesis:

- Traffic oscillations can appear regularly in the UK, the USA and Germany.
- Traffic oscillations can occur every 10 – 30 minutes on the A9 (Germany), every 3 – 6 minutes on OR 217 (USA) and every 8 – 12 minutes on the M4 (UK).
- The frequency of traffic oscillations in Germany is lower than in the USA.
- Traffic oscillations usually have higher amplitudes in Germany than in the USA.
- Traffic oscillations are more distinct in Germany than in the USA, i.e. they can be detected more easily.
- Traffic oscillations propagate at about 16 km/h on the A9 (Germany), at about 19 – 20 km/h on OR 217 (USA) and at about 14 km/h on the M4 (UK).
- Traffic oscillations propagate faster in the USA than in Germany.
Country specific analysis of oscillating congested traffic

Contents

CHAPTER 1  INTRODUCTION ................................................................................................................. 1

CHAPTER 2  BACKGROUND .................................................................................................................... 3

2.1  DEFINITION ........................................................................................................................................ 3

2.1.1  Definition from literature review ................................................................................................. 3

2.1.2  Definition applied ......................................................................................................................... 4

2.2  REASONS FOR OSCILLATIONS ............................................................................................................. 5

2.2.1  Traffic oscillations due to car-following behavior ..................................................................... 6

2.2.2  Traffic oscillations due to lane changing .................................................................................... 8

2.3  CHARACTERISTICS OF TRAFFIC OSCILLATIONS .................................................................................. 9

2.3.1  Amplitude of oscillations .............................................................................................................. 9

2.3.2  Propagation of oscillations ........................................................................................................ 10

2.3.3  Frequency of oscillations ........................................................................................................... 12

CHAPTER 3  DESCRIPTION OF THE DATA ....................................................................................... 15

3.1  OR 217 – SOUTHBOUND .................................................................................................................. 16

3.2  A9 – NORTHBOUND ......................................................................................................................... 17

3.3  M4 – EASTBOUND ............................................................................................................................ 18

CHAPTER 4  METHODOLOGY .............................................................................................................. 20

4.1  DETECTION OF CONGESTION ............................................................................................................ 21

4.2  MAUCH METHOD .............................................................................................................................. 22

4.2.1  Identification of propagation speed ........................................................................................... 25

4.3  CROSS-CORRELATION METHOD ....................................................................................................... 26

4.4  AUTOCORRELATION METHOD .......................................................................................................... 29

4.5  FOURIER TRANSFORMATION ............................................................................................................ 30

CHAPTER 5  ANALYSIS ........................................................................................................................... 31

5.1  DETECTION OF JAMS ........................................................................................................................ 31

5.2  VISUAL DETECTION .......................................................................................................................... 32

5.3  VELOCITY BY CROSS-CORRELATION ............................................................................................... 33

5.3.1  Cross-correlation Analysis for the M4 ...................................................................................... 34

5.3.2  Cross-correlation Analysis for OR 217 ..................................................................................... 36

5.3.3  Cross-correlation Analysis for A9 ............................................................................................. 38

5.4  CYCLE TIME BY AUTOCORRELATION ............................................................................................... 40

5.4.1  Autocorrelation method applied to M4 Data ............................................................................. 42

5.4.2  Autocorrelation method applied to OR 217 Data ...................................................................... 43
## List of figures

<table>
<thead>
<tr>
<th>Figure 2-1</th>
<th>Definitions of traffic oscillations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2-2</td>
<td>Definition of one oscillation</td>
</tr>
<tr>
<td>Figure 2-3</td>
<td>Causes of traffic oscillations</td>
</tr>
<tr>
<td>Figure 2-4</td>
<td>Formation of traffic oscillations by lane changing</td>
</tr>
<tr>
<td>Figure 2-5</td>
<td>Increasing effect of on–ramps on amplitude</td>
</tr>
<tr>
<td>Figure 2-6</td>
<td>Influence of site on oscillation frequency</td>
</tr>
<tr>
<td>Figure 3-1</td>
<td>Site map of OR 217 – Southbound; (Distances are given in m)</td>
</tr>
<tr>
<td>Figure 3-2</td>
<td>Site map for A9</td>
</tr>
<tr>
<td>Figure 3-3</td>
<td>Site map for M4</td>
</tr>
<tr>
<td>Figure 4-1</td>
<td>Overview of applied methods</td>
</tr>
<tr>
<td>Figure 4-2</td>
<td>Illustration of Mauch method</td>
</tr>
<tr>
<td>Figure 4-3</td>
<td>Illustration of Mauch method by relation 4-2</td>
</tr>
<tr>
<td>Figure 4-4</td>
<td>Demonstration of Mauch method</td>
</tr>
<tr>
<td>Figure 4-5</td>
<td>Mauch method for identification of propagation velocity</td>
</tr>
<tr>
<td>Figure 4-6</td>
<td>Illustration of hypothetical oscillation</td>
</tr>
<tr>
<td>Figure 4-7</td>
<td>Cross–correlation coefficient over the shift in time</td>
</tr>
<tr>
<td>Figure 4-8</td>
<td>Illustration of cross– and autocorrelation</td>
</tr>
<tr>
<td>Figure 4-9</td>
<td>Illustration of autocorrelation applied to a periodic signal</td>
</tr>
<tr>
<td>Figure 5-1</td>
<td>Oscillations visualized by Mauch method</td>
</tr>
<tr>
<td>Figure 5-2</td>
<td>Correlation coefficient for data of detectors 7 and 8 on M4</td>
</tr>
<tr>
<td>Figure 5-3</td>
<td>Autocorrelation method applied to data from M4</td>
</tr>
<tr>
<td>Figure 5-4</td>
<td>Discrete Fourier transformation of velocity profile of M4, detector 8</td>
</tr>
<tr>
<td>Figure 5-5</td>
<td>Spectral analysis for velocity data of two adjacent detector stations</td>
</tr>
<tr>
<td>Figure 6-1</td>
<td>Conclusions if country specific difference in frequency exists</td>
</tr>
</tbody>
</table>

VI
## List of tables

<table>
<thead>
<tr>
<th>Table 2-1</th>
<th>Definition of traffic oscillations in literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2-2</td>
<td>Stability thresholds according to equation</td>
</tr>
<tr>
<td>Table 2-3</td>
<td>Definition of traffic oscillations in literature</td>
</tr>
<tr>
<td>Table 2-4</td>
<td>Propagation speed in the USA</td>
</tr>
<tr>
<td>Table 2-5</td>
<td>Propagation speed in Germany</td>
</tr>
<tr>
<td>Table 2-6</td>
<td>Propagation speed in other countries</td>
</tr>
<tr>
<td>Table 2-7</td>
<td>Cycle time of traffic oscillations according to literature</td>
</tr>
<tr>
<td>Table 3-1</td>
<td>Main characteristics of available data</td>
</tr>
<tr>
<td>Table 3-2</td>
<td>Precipitation for OR 217</td>
</tr>
<tr>
<td>Table 4-1</td>
<td>Interpretation of correlation coefficient</td>
</tr>
<tr>
<td>Table 5-1</td>
<td>Oscillation speed identified by Mauch method</td>
</tr>
<tr>
<td>Table 5-2</td>
<td>Propagation speed of oscillations for M4 identified by correlation method</td>
</tr>
<tr>
<td>Table 5-3</td>
<td>Velocity on OR 217, identified by cross–correlation method</td>
</tr>
<tr>
<td>Table 5-4</td>
<td>Results of cross–correlation method applied to non–adjacent detectors</td>
</tr>
<tr>
<td>Table 5-5</td>
<td>Wave velocity on A9, identified by cross–correlation method for adjacent detectors</td>
</tr>
<tr>
<td>Table 5-6</td>
<td>Velocity on A9, identified by cross–correlation method for the whole investigated part of the jam</td>
</tr>
<tr>
<td>Table 5-7</td>
<td>Classification of the results of the autocorrelation method</td>
</tr>
<tr>
<td>Table 5-8</td>
<td>Results of Autocorrelation method for M4</td>
</tr>
<tr>
<td>Table 5-9</td>
<td>Range, mean and median of the results of the autocorrelation method for M4</td>
</tr>
<tr>
<td>Table 5-10</td>
<td>Results of autocorrelation method for OR 217</td>
</tr>
<tr>
<td>Table 5-11</td>
<td>Range, mean and median of the results of the autocorrelation method for OR 217</td>
</tr>
</tbody>
</table>
Country specific analysis of oscillating congested traffic

Table 5-12 | Results of autocorrelation method for A9
Table 5-13 | Range, mean and median of the results of the autocorrelation method for A9
Table 6-1 | Average propagation speed
Table 6-2 | Magnitude of cycle times identified in this study

List of symbols and abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{v}_f$</td>
<td>m/s^2</td>
<td>acceleration of the following vehicle</td>
</tr>
<tr>
<td>$v_f$</td>
<td>m/s</td>
<td>velocity of the following vehicle</td>
</tr>
<tr>
<td>$v_p$</td>
<td>m/s</td>
<td>velocity of the preceding vehicle</td>
</tr>
<tr>
<td>$T$</td>
<td>s</td>
<td>driver’s reaction time</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>1/s</td>
<td>driver’s sensitivity</td>
</tr>
<tr>
<td>$S(t)$</td>
<td>km</td>
<td>traffic velocity cumulated over time</td>
</tr>
<tr>
<td>$\tau$</td>
<td>min</td>
<td>time constant used for Mauch method</td>
</tr>
<tr>
<td>$\tau_k$</td>
<td>–</td>
<td>constant used for Mauch method</td>
</tr>
<tr>
<td>$\overline{S}_f(t)$</td>
<td>km</td>
<td>cumulated velocity if speed was constant for $[t-\tau, t+\tau]$</td>
</tr>
<tr>
<td>$D(t)$</td>
<td>km</td>
<td>deviation detected by Mauch method</td>
</tr>
<tr>
<td>$q_{down}$</td>
<td>vehicles / h</td>
<td>Flow at downstream location</td>
</tr>
<tr>
<td>$q_{up}$</td>
<td>vehicles / h</td>
<td>Flow at upstream location</td>
</tr>
<tr>
<td>$c$</td>
<td>–</td>
<td>constant; ratio between $q_{down}$ and $q_{up}$</td>
</tr>
<tr>
<td>LWR</td>
<td></td>
<td>Lighthill–Whitham–Richards</td>
</tr>
</tbody>
</table>
Chapter 1   Introduction

In order to maintain and increase the safety, predictability and efficiency of the transportation system, major investments were made in the past leading to the construction of additional road infrastructure. Nowadays economic and political reasons limit the possibility of building new facilities. Instead, more “intelligent” operations are the focus. Since their development and deployment requires a thorough understanding of the traffic flow, research has been performed resulting in various traffic models.

One of them is the Lighthill–Witham–Richards (LWR) model. It is based on a fundamental diagram [1] and can describe the propagation of perturbations in the flow.

Sometimes such perturbations appear regularly, commonly referred to as traffic oscillations. It has been found, that they can grow in amplitude while propagating upstream, a finding that cannot be described by the LWR – fundamental diagram [2]. This is one factor that has led to new modeling approaches. However, these are still not satisfactory, since further inconsistencies exist [2]. As traffic oscillations are a main driver for criticizing the LWR – approach and hence developing new models, they require special focus. Thus a better understanding of them might help solve some of the remaining questions.

Different countries have different standards for infrastructure, vehicle mix and driving rules; driver behavior may also vary. As a result, traffic flow might reveal different characteristics. Hence, if such differences are detected, conclusions on the effects of these stan-
Country specific analysis of oscillating congested traffic

dards might be possible leading to a greater understanding. Therefore this thesis aims at a
country specific analysis of traffic oscillations.

The thesis begins with a definition of traffic oscillations in Chapter 2. The results of pre-
vious analysis are also explained in this section and hence an overview of the current
knowledge in the field is presented.

Loop detector data was available for this research. The corresponding sites are described in
Chapter 3.

Different methods have been applied to this data in order to identify and quantify characte-
ristics of traffic oscillations. They are described in chapter 4.

The results are presented in chapter 5.

Results are summarized and discussed in chapter 6. A comparison leads to statements on
country specific characteristics.
Chapter 2  Background

2.1  Definition

2.1.1  Definition from literature review

In the available literature [2, 3, 4, 5], different definitions of traffic oscillations are given. As illustrated in figure 2-1, they can be grouped into three classes A, B and C.

Figure 2-1: Definitions of traffic oscillations

If flow is a function of traffic speed, definitions A and B are interchangeable.

The different definitions are given more precisely in table 2-1.
Table 2-1: Definition of traffic oscillations in literature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Definition</th>
<th>Class</th>
<th>Analysis based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>Sharp increase in flow followed by a sharp reduction in flow</td>
<td>A</td>
<td>flow</td>
</tr>
</tbody>
</table>
| [4]       | Stop–and–go driving motions                                               | B     | a) travel time (which is directly related to speed)  
b) flow |
| [2]       | Oscillating congested traffic is one of 5 different states of congestion and “shows more or less regular oscillations of speed with a frequency and amplitude which stay roughly constant over a certain period of time.” | C     |                                |

2.1.2 Definition applied

A pattern in traffic flow will be referred to as a traffic oscillation if:

- *the space–mean speed of a short road section drops, rises and drops again over time* (cf. [1,6] for a definition of space–mean speed, also referred to as traffic speed in this thesis),

- *the traffic is congested* (cf. [7] for definition of congestion, also referred to as jammed or queued traffic in this thesis) and

- *it propagates upstream* against the direction of travel.
For illustration purpose, figure 2-2 shows a hypothetical traffic oscillation.

Figure 2-2: Definition of one oscillation

Figure 2-2 also illustrates the amplitude of a traffic oscillation. More precisely it will be defined as:

\[
\text{Amplitude} = \frac{1}{2} (\text{maximum speed} - \text{minimum speed}).
\]

### 2.2 Reasons for oscillations

Previous research has investigated possible reasons for traffic oscillations. Two related explanations are illustrated in figure 2-3 and described in more detail in the following sections.
Country specific analysis of oscillating congested traffic

Figure 2-3: Causes of traffic oscillations

2.2.1 Traffic oscillations due to car–following behavior

Microscopic car–following models are often used to explain traffic oscillations [6, 8, 9, 10]. Analysis reveals the influence of various parameters on the stability of the traffic flow. Stability is defined in [9] as following.

- "Local Stability is concerned with the response of a following vehicle to a fluctuation in the motion of the vehicle directly in front of it; i.e., it is concerned with the localized behavior between pairs of vehicles."

- "Asymptotic Stability is concerned with the manner in which a fluctuation in the motion of any vehicle, say the lead vehicle of a platoon, is propagated through a line of vehicles."

Analytical analysis of stability:

In [9, 10] the behavior of a vehicle following another one is analyzed analytically based on the following model:

\[ \dot{v}_f(t + T) = \lambda \cdot (v_p(t) - v_f(t)) \]  \hspace{1cm} (2-1)

with:

- \( \dot{v}_f \): the acceleration of the following vehicle,
- \( v_f \): the velocity of the following vehicle,
- \( v_p \): velocity of the preceding vehicle,
- \( T \): driver’s reaction time and
- \( \lambda \): the driver’s sensitivity.

It is shown that stability depends on the product \( \lambda \cdot T \). Table 2-2 gives the thresholds.
Country specific analysis of oscillating congested traffic

<table>
<thead>
<tr>
<th>Locally unstable</th>
<th>Asymptotically unstable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda \cdot T &gt; 0.5 \pi$</td>
<td>$\lambda \cdot T &gt; 0.5$</td>
</tr>
</tbody>
</table>

Unstable: Motion is oscillatory with increasing amplitude.

Table 2-2: Stability thresholds according to equation (2-1)

This indicates that long reaction times as well as a high sensitivity of the driver are reasons for traffic oscillations.

Analysis by simulation:

Stability is discussed in [8] by simulation with a more sophisticated model. Analysis is performed in regards to three different times which are explained in the following table.

<table>
<thead>
<tr>
<th>Reaction time</th>
<th>The time lag between the traffic situation and the driver’s reaction to it.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update time</td>
<td>If a driver perceives the traffic situation only at discrete moments in time, the time gap between these moments is referred to as update time.</td>
</tr>
<tr>
<td>Velocity adaptation time</td>
<td>The time needed to reach the desired speed. Since this time depends directly on the acceleration of the vehicle, it is regarded as the corresponding value of the driver’s sensitivity in equation (2-1). (Note that the driver’s sensitivity linearly affects the acceleration.)</td>
</tr>
</tbody>
</table>

Table 2-3: Reaction time, update time and velocity adaptation time

Similarly to [9, 10] the results support that:

- a high reaction time and
- a low velocity adaptation time (corresponding to a high driver’s sensitivity in equation (2-1)) can result in instability.

Furthermore it is found that:

- the effect of the update time on stability is similar to the effect of the reaction time for “update time = ½ reaction time” and
- a very high adaptation time (corresponding to a very low driver’s sensitivity in equation (2-1)) leads to instability, independent of reaction or update time.

### 2.2.2 Traffic oscillations due to lane changing

In [4] lane changing is identified as the primary factor for traffic oscillations. Accordingly oscillations can form and increase in amplitude if:

- a vehicle merges between two other vehicles and
- these vehicles are following closely.

The formation of oscillations by lane changing is illustrated in figure 2-4.

**Figure 2-4:** Formation of traffic oscillations by lane changing (picture source: [4]). The movement of vehicles (solid lines) is plotted over space and time for one freeway lane. Shortly after 14:59:35 two vehicles (solid green lines) merge into the observed lane. This causes the following vehicle (solid black line) to reduce its speed. The perturbation then travels upstream as illustrated by the dashed red lines.
2.3 Characteristics of traffic oscillations

2.3.1 Amplitude of oscillations

Growth of oscillations:

Car-following-models (cf. [6, 8, 9, 10], chapter 2.2.1) and empirical observations [4] show that oscillations increase in amplitude while propagating upstream. (In [4] a measure other than amplitude was used. However, a relation between this measure and amplitude seems intuitively correct and therefore is assumed for this and the following statement.)

Effect of ramps:

In [4] it was found that on–ramps have an effect on the amplitude of traffic oscillation.

This is explained by use of the following two assumptions:

1. Two congested flows (e.g. ramp flow and freeway flow) merge at a constant ratio and

2. a relation between flow and speed exists.

Assumption 1 yields to (cf. Appendix A 1 for detailed explanations):

\[ q_{\text{down}} = c \cdot q_{\text{up}}. \]  \hspace{1cm} (2-2)

(Where \( q_{\text{down}} \) is flow at a downstream location and \( q_{\text{up}} \) is the flow at an upstream location; \( c \) is a constant.)

As can be seen in figure 2-5, this yields to a decrease in amplitude if a traffic oscillation propagates upstream past an on–ramp.

Similarly, off–ramps are likely to have an increasing effect on traffic oscillations. However, no validation has been performed for this case in [4].
Figure 2-5: Increasing effect of on–ramps on amplitude. As can be seen, the difference in flow is larger downstream than upstream. Since there is a relation between flow and speed, this affects the amplitude of oscillations.

2.3.2 Propagation of oscillations

Propagation speed:

Oscillations are perturbations in the flow of congested traffic. Various studies (cf. tables 2-4, 2-5 and 2-6) have revealed that they travel at characteristic velocities, also referred to as wave speed.

A definition of a wave is given in [1]. A wave separates two different traffic states. Such a state is characterized by its traffic velocity. (Since a relation between flow, speed and density is assumed in [1], a state can also be described by use of flow or density). By definition (cf. chapter 2.1.2), oscillations are characterized by a decrease of traffic speed fol-
Country specific analysis of oscillating congested traffic

allowed by an increase and then by a decrease of the speed. Therefore it combines several traffic states. As a result, the propagation speed of a traffic oscillation is the same as the wave speed.

Waves in congested traffic were found to propagate against the direction of travel. Their speed hereby is fairly constant and independent of ramps ([3, 4, 5]). Characteristic speeds identified in various studies can be found in tables 2-4, 2-5 and 2-6.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Year data was obtained</td>
<td>2003</td>
<td>not available</td>
<td>not available</td>
<td>2003</td>
<td>1966</td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td>Berkeley Highway Laboratory, I – 80 East-bound (California)</td>
<td>I – 880</td>
<td>Holland Tunnel</td>
<td>Berkeley Highway Laboratory, I – 80 Eastbound</td>
<td>John C. Lodge Freeway (near Detroit, MI)</td>
<td>no site, general statement</td>
</tr>
<tr>
<td>Velocity [km/h]</td>
<td>18 – 21</td>
<td>19.6</td>
<td>17.1</td>
<td>90 % between 15 and 25</td>
<td>26</td>
<td>about 20</td>
</tr>
<tr>
<td>Comment</td>
<td>same site as in [13]</td>
<td>Referred to by [5]</td>
<td></td>
<td></td>
<td>imprecise measuring</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-4: Propagation speed in the USA

<table>
<thead>
<tr>
<th>Study</th>
<th>[2]</th>
<th>[3]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year data was obtained</td>
<td>2001</td>
<td>2001</td>
</tr>
<tr>
<td>Site</td>
<td>A 5</td>
<td>A 5</td>
</tr>
<tr>
<td>Velocity [km/h]</td>
<td>15.7 ±1.2</td>
<td>17.7</td>
</tr>
<tr>
<td>Comment</td>
<td>same site as in [3]</td>
<td>Standard deviation: 0.9 km/h</td>
</tr>
</tbody>
</table>

Table 2-5: Propagation speed in Germany
Country specific analysis of oscillating congested traffic

<table>
<thead>
<tr>
<th>Year data was obtained</th>
<th>1998</th>
<th>1998</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Queen–Elizabeth–Way (Ontario, Canada)</td>
<td>M4 (United Kingdom)</td>
</tr>
<tr>
<td>Velocity [km/h]</td>
<td>20 – 24</td>
<td>17.6 – 19.2</td>
</tr>
<tr>
<td>Comment</td>
<td>same site as in this thesis</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-6: Propagation speed in other countries

As indicated by tables 2-4 and 2-5, the propagation speed is lower for German sites than for American. Although no further evidence was found in the literature, this statement was confirmed in verbal discussion by Dr. Martin Treiber from Dresden University of Technology, Germany.

Lateral propagation of oscillations:

According to analysis in [4] oscillations appear in adjacent lanes shortly after they were first detected.

2.3.3 Frequency of oscillations

Oscillations often occur regularly [2]. Therefore they can be characterized by their frequency; its reciprocal value will be referred to as cycle time.

Table 2-6 gives the result of a literature review on the cycle time.

In [3, 4, 5] a frequency analysis was not object of the analysis. The values were obtained by visual analysis of the graphs presented in the studies and hence they lack precision and objectivity. Furthermore, it is possible that the methodology applied in these works amplifies certain frequencies and suppresses others (the applied methodology is explained in chapter 4.2).

Despite these deficiencies, table 2-6 does suggest that oscillation frequency is lower for European sites than for North American ones. Therefore the analysis in Chapter 5 includes an investigation of the frequency.
## Country specific analysis of oscillating congested traffic

<table>
<thead>
<tr>
<th>Study</th>
<th>Cycle time [min]</th>
<th>Study site</th>
<th>Year data was obtained</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>[12]</td>
<td>3</td>
<td>USA (Holland Tunnel)</td>
<td>not available</td>
<td>Frequency directly upstream of the bottleneck (high frequencies might fade out upstream as explained below)</td>
</tr>
<tr>
<td>[4]</td>
<td>4 – 8</td>
<td>USA (I–80)</td>
<td>2003</td>
<td>Frequency analysis was not object of analysis. Results were obtained by looking at the plots</td>
</tr>
<tr>
<td>[14]</td>
<td>4</td>
<td>USA (J. C. Lodge Freeway)</td>
<td>1966</td>
<td>–</td>
</tr>
<tr>
<td>[5]</td>
<td>6 – 8</td>
<td>Canada (Queen–Elizabeth–Way)</td>
<td>1998</td>
<td>Frequency analysis was not object of analysis. Results were obtained by looking at the plots</td>
</tr>
<tr>
<td>[3]</td>
<td>ca. 20</td>
<td>Germany (A 5)</td>
<td>2001</td>
<td>Frequency analysis was not object of analysis. Results were obtained by looking at the plots</td>
</tr>
<tr>
<td>[9]</td>
<td>5.5/7.5/15/16</td>
<td>Germany (A 5)</td>
<td>not available</td>
<td>Oscillations were not chosen arbitrarily, They were chosen to demonstrate the effect of different cycle times on the amplitude, hence they might not show typical values</td>
</tr>
</tbody>
</table>

**Table 2-7: Cycle time of traffic oscillations according to literature**

### Relation between Amplitude and Frequency:

A relation between amplitude and frequency is stated in [9]. Accordingly, long cycle times are accompanied with large amplitudes. Respectively high frequencies result in low amplitudes.
Fading of high frequencies:

A car–following model is described in [17]. Accordingly, oscillations with small frequencies fade out whereas those with low frequencies grow in amplitude while they propagate upstream.

Relation between frequency and flow:

According to [2], the cycle time of oscillations is dependent on flow. It is further stated that oscillations don’t exist in very low traffic flow [2, 5].

As illustrated in figure 2-6, flow in congestion is restricted by a site specific bottleneck. Since flow is believed to be one influence factor of the oscillation frequency, different sites are likely to show different frequencies.

Figure 2-6: Influence of site on oscillation frequency
Chapter 3   Description of the data

In order to draw conclusions on reproducible characteristics of traffic oscillations, loop detector data was analyzed for this study. Data was available from sites in Germany, the USA and the United Kingdom. Its main characteristics are summarized in table 3-1. Site maps are presented in figures 3-1, 3-2 and 3-3 on the following pages where further details are given. It shall be noted that a new numbering of the detectors was introduced. A key relating the new labeling to the old one can be found in Appendix A 1.

The data itself is also available on the CD attached to this work.

<table>
<thead>
<tr>
<th>Site</th>
<th>Aggregation time</th>
<th>Measured values</th>
<th>Length of investigated site</th>
</tr>
</thead>
<tbody>
<tr>
<td>OR 217 (USA)</td>
<td>20 s</td>
<td>flow, velocity, occupancy</td>
<td>11.2 km</td>
</tr>
<tr>
<td>A9 (Germany)</td>
<td>1 min</td>
<td>flow, velocity</td>
<td>15.9 km</td>
</tr>
<tr>
<td>M4 (United Kingdom)</td>
<td>no aggregation</td>
<td>vehicle arrival time, velocity</td>
<td>6.8 km</td>
</tr>
</tbody>
</table>

*Table 3-1: Main characteristics of available data*
3.1 OR 217 – Southbound

OR 217 is a freeway southwest of Portland, Oregon in the USA connecting I 5 and US 26. Data was available for the whole section. It was downloaded from PORTAL [18], an online data archive for the Portland metropolitan area. Analysis was done for the southbound direction. Velocity, count and occupancy information was available for the freeway lanes as well as for the on ramps in 20 second aggregates. Sensors on off–ramps were not installed. A sitemap is given in figure 3-1.

Figure 3-1: Site map of OR 217 – Southbound; (Distances are given in m)

Measurement of velocity:

The data was provided by double loop detectors. However, there was uncertainty whether the velocity was directly measured by these detectors or if other information such as flow and occupancy was used to identify the traffic speed.

Ramp metering:

A ramp metering system is active on every on–ramp of this site. It was running on a fixed-time basis for the analyzed days. (It has been changed to a traffic adaptive algorithm in November 2005.)

Detector locations:

Since the available detector locations were inaccurate, their location was identified using video logs available at the homepage of the Oregon Department of Transportation at [19]
(Video logs for January 9th, 2003 and September 29th, 2003 were used, respective images are available on the CD attached to this work).

Weather:

Weather information was available from [18]. Information on the precipitation is summarized in table 3-2. The temperatures were above freezing for all days. On September 1st, a temperature of 30 °C was reached being the hottest of all days.

<table>
<thead>
<tr>
<th>Detector pair</th>
<th>3.8.05</th>
<th>4.18.05</th>
<th>9.1.05</th>
<th>9.16.05</th>
<th>9.16.05</th>
<th>9.22.05</th>
<th>9.26.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>precipitation</td>
<td>none</td>
<td>4 am – 7 am</td>
<td>none</td>
<td>none</td>
<td>4 pm – 5 pm</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 3-2: Precipitation for OR 217

3.2 A9 – Northbound

The investigated part of the German freeway A9 is north of Munich. Data was available from double loop detectors between km 528.2 and km 513.3, i.e. mainly between the access points “Frankfurter Ring” and “Neufahrn.” Sensor information includes data from on– and off–ramps and consists of velocity and flow aggregated over 1 min periods. A site map is given in figure 3-2. The freeway is equipped with variable message signs and a variable speed limit system. Their location is illustrated in the sitemap.

Figure 3-2: Site map for A9

Weather:

According to [20], there was no precipitation on any of the analyzed days. No extreme temperatures were present either.
3.3 **M4 – Eastbound**

The M4 runs eastbound to London in the United Kingdom. Data was available for the section between km 23.2 and km 16.2 (i.e. between junction 3 and 2) for November 1998. Since a bus lane was introduced in 1999, the site does not exist with this configuration anymore.

Figure 3-3 shows a sitemap before the changes, at the time when the data was created.

![Site map for M4](image-url)

*Figure 3-3: Site map for M4*

It shall be noted, that some inconsistencies exist:

- Detector locations as well as the distance between them were available separately. They were not always equal. Small-scale errors existed. This is believed to be due to rounding errors. For further analysis, the distance between the detectors was used.

- Discrepancies between the data sets and an available site map exist. According to this sitemap there are three lanes at detector location 2. However, data only existed for two lanes and it seems unlikely that one lane is not equipped with detectors while the others are. Figure 3-3 shows the site according to the data sets.

- A detector at location 2 was malfunctioning. Since its data was only used for creating speed-contour plots (cf. Appendix A 4.1 for examples), it was neglected. Thus only the remaining detector was used to identify the traffic speed.

**Aggregation:**

Since the analysis pursued is based on a macroscopic approach, aggregation was necessary. It was done arbitrarily for 10 s intervals.
Weather:

According to [20] no precipitation was present for the analyzed days and temperatures were above freezing.
Chapter 4 Methodology

This thesis aims at a country specific comparison of traffic oscillations. According to the task sheets, the following steps have to be taken:

1. Detection of oscillations and
2. Identification of parameters describing the oscillations

Therefore this chapter describes different methods that are applied for the analysis. A brief overview of these methods is given in figure 4-1. They are explained in detail in the following sections.

In this thesis, traffic oscillations are defined by space–mean speed (cf. chapter 2.1.2). Since only time–mean speed was available, all analysis is based on the assumption, that space–mean speed can be described sufficiently by time–mean speed.

Furthermore, oscillations are believed to propagate laterally to adjacent lanes (cf. chapter 2.3.2). Therefore analysis has been performed on the average velocity (arithmetic mean) over all lanes.
Country specific analysis of oscillating congested traffic

4.1 Detection of congestion

By definition (cf. chapter 2.1.2) traffic oscillations only exist in congestion. Therefore congestion first has to be identified in order to detect them.

Since congestion is accompanied by slow moving vehicles, low velocities can indicate queued traffic conditions. Hence, plotting speed over time and space can reveal congested areas.

However, slow traffic might also be due to other factors (e.g. speed limits, construction). Therefore a different method is explained and applied in [3, 5, 15, 21, 22, 23, 24]. This method additionally uses flow for jam detection.
Oscillations are perturbations in the traffic flow (c.f. chapter 2.1.2) which usually appear regularly. Since such patterns are typical for congestion but not for uncongested traffic [5, 15], this reduces the possibility of drawing false conclusion due to incorrectly interpreting low velocities as jams.

4.2 Mauch method

Traffic oscillations have been studied in [3, 4, 5, 15, 16]. The methodology used in these works is also applied in this thesis and will be referred to as Mauch method.

The Mauch method is based on the following equation.

\[
D(t) = S(t) - \frac{S(t - \tau) + S(t + \tau)}{2} 
\]

with:
- \(S(t)\): the cumulated velocity at time \(t\): \(S(t) = \int_{t_0}^{t} v(t') \, dt'\) 
  \((v(t): \text{traffic velocity at time } t; t_0: \text{time at beginning of observation})\)
- \(\tau\): time constant and
- \(D(t)\): Deviation detected by the Mauch method (further explanations are given below).

(In [3, 4, 5, 15, 16] the analysis is based on flow instead.)

In order to explain the methodology a hypothetical velocity profile is assumed and its cumulated values are plotted over time. This is illustrated in figure 4-2. It can be seen that equation 4-1 can be interpreted as:

\[
D(t) = S(t) - \frac{S(t - \tau) + S(t + \tau)}{2} \cdot \frac{1}{S_\tau(t)}
\]

Difference between these cumulated velocities  
cumulated velocity  
cumulated velocity if speed is assumed constant for \([t-\tau; t+\tau]\)
Figure 4-2: Illustration of Mauch method. A hypothetical velocity profile is assumed. The cumulated speed is plotted over time. As can be seen, the Mauch method detects the difference between the actual cumulated velocity and the cumulated velocity if the traffic speed was constant for \([t-\tau, t+\tau]\).

A different interpretation can be obtained if equation 4-1 is transformed (cf. Appendix A 3 for transformations). These transformations yield to

\[
D(t) \sim \int_{t-\tau}^{t} v(t') \, dt' - \int_{t}^{t+\tau} v(t') \, dt' \tag{4-2}
\]

Relation 4-2 shows, that the deviation \(D(t)\) can be calculated by the difference of the areas marked by the solid green and the dashed red lines in figure 4-3.
Figure 4-3: Illustration of Mauch method by relation 4-2. As can be seen, \( D(t) \) can be calculated by the difference of the areas marked by the red dashed lines area marked by the green solid lines.

Relation 4-2 and figure 4-3 suggest that the deviation \( D(t) \) has a maximum peak if a transition from high to low traffic velocity takes place. Respectively it has a minimum if there is an increase from low to high speed. Therefore the methodology can be used in a heuristic way in order to detect traffic oscillations.

Since only discrete values of the traffic velocity are available for this thesis, equation 4-1 is applied in the following form:

\[
D(k) = \frac{\sum_{i=k_0}^{k-\tau} (v_i \cdot \Delta t) + \sum_{i=k_0}^{k+\tau} (v_i \cdot \Delta t)}{S(k) + \frac{2}{\sum_{\tau} \tau_k(k)}}
\]  

(4-3)

with:
- \( \Delta t \): sampling period or aggregation period (constant value in this analysis),
- \( k \): enumerator referring to the current sample
- \( k_0 \): sample at which observations begin
- \( v_i \): traffic velocity for sample \( i \)
- \( \tau_k \): constant with \( \tau_k = \frac{\tau}{\Delta t} \)
In this thesis $\tau_k$ is chosen that $\tau = 7 \text{ min}$.

Figure 4-4 illustrates the method for real velocity data. The deviation $D(t)$ is represented by the green line. For comparison, the 10 s velocity, the oblique velocity and the oblique flow are plotted (information on oblique plots can be found in [21, 22, 25].

Data from the M4 (November 2, 1998, 18:38 – 19:24) was used.

4.2.1 Identification of propagation speed

In [3, 4, 5, 15, 16] the Mauch method has been applied in order to identify the propagation speed of oscillations. Therefore the deviation $D(t)$ has been plotted over time for various detectors. The different plots can be located vertically with the distance between each curve proportional to the distance between the detectors on the freeway. This is demonstrated in figure 4-5.
The propagation of the oscillations is illustrated by the solid straight lines. The dashed lines show other possible interpretations of their propagation. Thus the velocities obtained by this method are based on subjective interpretation.

Figure 4-5: Uncertainty of Mauch method for identification of propagation velocity.
(About 20 minutes of data from detectors 6 and 7 on the M4, November 2, 1998 were used to create the plot.)

4.3 Cross–correlation method

In the previous section a method was introduced to visualize traffic oscillations. It was shown that this method can be used to identify their propagation velocity. However, it was demonstrated, that this is based on subjective interpretation. Therefore a different method is presented following, which will be referred to as the Cross–correlation method and was used similarly in [13, 14].

Since oscillations propagate through the freeway network (cf. chapter 2.1.2), the same oscillations can be identified in the data measured at adjacent detector stations.

For demonstration purposes a traffic oscillation is assumed, measured at two detector locations A (downstream) and B (upstream). The hypothetical data is plotted in figure 4-6. As illustrated, both data sets match if one of them is shifted in time appropriately. This shift is the travel time of the oscillation from detector A to detector B.
Figure 4-6: Illustration of hypothetical oscillation; as can be seen, they match if one of them is shifted in time.

Due to noise, aggregation and other influence factors, the velocity profile at the two detector stations will not perfectly match. In order to quantify how similar the data sets are, the correlation coefficient $r_{xy}$ between them can be calculated. The calculation rule can be found in [26]. Accordingly, the following interpretations can be made:

<table>
<thead>
<tr>
<th>$r_{xy} = -1$</th>
<th>$r_{xy} = 0$</th>
<th>$r_{xy} = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>negative correlation</td>
<td>no correlation</td>
<td>positive correlation</td>
</tr>
<tr>
<td>an increase in one data set corresponds linearly to a decrease in the other data set</td>
<td>the data sets are linearly independent of each other</td>
<td>an increase in one data set corresponds linearly to an increase in the other data set</td>
</tr>
</tbody>
</table>

Table 4-1: Interpretation of correlation coefficient
Figure 4-7 plots the correlation coefficient over the time shift for the example shown in figure 4-6.

![Figure 4-7: Cross-correlation coefficient over the shift in time. It is demonstrated for the example illustrated in figure 4-6.](image)

A peak can be identified. The respective time shift is interpreted as the travel time of the hypothetical oscillation between the detectors. If the distance between the detectors is known, the wave velocity (and in conclusion the oscillation velocity) can be calculated.

The previous explanations were based on one hypothetical traffic oscillation. If real data is used, the following aspects must be considered:

- Since artificial data was used for demonstration, the data sets match perfectly for a certain time shift and the corresponding correlation coefficient in figure 4-7 is 1. However, oscillations are subject to the influence of different factors while propagating upstream and measurements are noisy, therefore the correlation coefficient is expected to be less than 1. Nevertheless, a peak shall still exist.

- The methodology does not take into account that different waves might travel at different velocities. Since previous studies have not found large deviations in the
wave speed in congested traffic (cf. chapter 2.3.2), these differences are expected to be low. The result obtained is assumed to be an average travel time.

- Data sets can only be compared for a time shift which is a multiple of the aggregation time. Hence, the travel time and therefore the propagation velocity obtained by this method are discrete.

4.4 Autocorrelation method

For the Cross–correlation method, two different data sets (i.e. data from two different locations) are compared. If one data set is compared with itself, shifted in time, this will be referred to as autocorrelation. Cross– and autocorrelation are illustrated in figure 4-8.

\[
\text{Cross – correlation} \quad \begin{cases} 
\text{Data A} \\
\text{Data B} 
\end{cases} 
\]

\[
\text{Auto-} \\
\text{correlation} \quad \begin{cases} 
\text{Data A} \\
\text{Data A} 
\end{cases} 
\]

\[
\text{Time} \\
\text{shift} \\
\text{calculation of} \\
\text{correlation} \\
\text{Different data} \\
\text{from different locations} \\
\text{Time} \\
\text{shift} \\
\text{calculation of} \\
\text{correlation} \\
\text{same data} \\
\text{only shift in time} \\
\text{Data A} \\
\text{Data A} 
\]

*Figure 4-8: Illustration of cross– and autocorrelation*

According to [27] periodic components of a signal can be identified by autocorrelation. This is demonstrated in figure 4-9 in which a hypothetic periodic signal is illustrated. As shown, it matches with itself if it is shifted in time by a multiple of the cycle time.
Figure 4-9: Illustration of autocorrelation applied to a periodic signal. As illustrated, the signal matches to itself if it is shifted by the cycle time. Hence, the autocorrelation function will have a peak for a multiple of the cycle time.

Therefore a peak in the autocorrelation of the data indicates that it repeats itself to certain extend after the respective time shift.

Hence, periodicity of the autocorrelation allows conclusion on the periodicity of the original data. Thus the cycle time can be identified by the time shift corresponding to a peak. A similar approach was used in [14] (the power density spectrum (i.e. the Fourier transformation of the autocorrelation) was used instead of the autocorrelation).

4.5 Fourier Transformation

The Fourier transformation is a mathematical method used to express a signal as a sum of sine and cosine functions. This method has received special importance since these functions can be interpreted as frequencies. Further information on the Fourier transformation can be found in the literature. For this thesis [28] was available.
Chapter 5  Analysis

In this chapter the previously explained methodologies are applied to traffic data.

Results are shown for one jam (M4, November 2, 1998, 18:31 – 19:31) in detail and in condensed form for the other days and sites. The plots and graphs used for their analysis can be found in the Appendix and on the CD attached to this work.

5.1 Detection of jams

As explained in chapter 2.1.2, congested traffic is first identified. Therefore the following two steps are taken:

1. Identification of low speed regimes using a time–space diagram of the measured traffic speed. These diagrams can be found in Appendix A 4.

2. Verification of the low speeds by plotting them over time for each detector. These plots can be found in Appendix A 5.

All further analysis has been performed with data identified as congested by this method.
5.2 Visual detection

In order to visualize oscillations the Mauch method (cf. chapter 4.2) has been applied to the data. Figure 5-1 shows the results.

![Figure 5-1: Oscillations visualized by Mauch method (M4; Nov. 2nd, 1998; 18:38 to 19:24)](image)

**Observations:**

a) Oscillations occur regularly.

b) Oscillations occur and propagate upstream against the direction of travel. This is illustrated by lines which represent waves. The slope of these lines represents the propagation velocity of these waves.

c) The travel time of the waves can be identified. Since the distance between the detectors is known, the wave velocity can be calculated. It is given by the slope of the lines. Table 5-1 gives the speed referring to the slope of each line (and in conclusion to each wave).
d) As can be seen in table 5-1, the oscillations propagate at similar speeds. Their arithmetic mean speed is 14.2 km/h, their median is 14.4 km/h.

e) The cycle time is between 10 and 13 minutes.

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation velocity [km/h]</td>
<td>15.3</td>
<td>15.3</td>
<td>15.7</td>
<td>14.4</td>
<td>13.2</td>
<td>11.1</td>
<td>14.1</td>
<td>14.2</td>
</tr>
</tbody>
</table>

*Table 5-1: Oscillation speed identified by Mauch method (M4, November 2, 1998 from 18:38 to 19:24).*

Oscillations were found for all sites by this method and hence can exist in all three countries. The plots can be found in Appendix A 6. Similar observations were made.

### 5.3 Velocity by cross-correlation

In the previous chapter the propagation speed was determined using subjective interpretation. In order to reduce the impact of this subjectivity, the Cross-correlation method (cf. chapter 4.3) is applied to the data.

Detectors 7 and 8 are used for the analysis (M4, November 2, 18:31 – 19:31). Therefore the data from the upstream location (detector 8) was shifted in time. The correlation coefficient is plotted in relation to the time shift in figure 5-2.

**Observations:**

a) The correlation coefficient reaches a peak of 0.68 for a time shift of 140 s.

b) There are further peaks for time shifts of 820 s, 1630 s and 2360 s. The peaks are 680 to 810 s apart.

**Interpretation:**

a) Oscillations need 140 s to propagate from detector 7 to detector 8. In conclusion, they travel at about 12.9 km/h.

b) The velocity profile also matches for larger time shifts. This is due to its periodicity. Further analysis on this is described in section 5.4.
Country specific analysis of oscillating congested traffic

Figure 5-2: Correlation coefficient for data of detectors 7 and 8 on M4, November 2, 1998 between 18:31 and 19:31. The correlation coefficient is plotted with respect to the time shift of the data.

By means of the cross-correlation method, the wave speed was identified. In the following sections, it is obtained for other detector pairs, other jams and other sites.

5.3.1 Cross-correlation Analysis for the M4

The previously demonstrated method was applied to the data of other detector pairs and other jams on the M4. The plots used for the following analysis can be found in Appendix A 7.1. Table 5-2 summarizes the results. Velocities are given in km/h. The numbers in brackets refer to the correlation coefficient of the corresponding time shift.
Table 5-2: Propagation speed of oscillations for M4 identified by correlation method (cf. chapter 4.3). The velocities are given in km/h and the numbers in brackets refer to the correlation coefficient of the appropriate time shift. The line labeled overall gives the results if the correlation of the most downstream and most upstream detector is calculated.

Observations and interpretations:

a) The propagation velocities are between 11.3 and 16.4 km/h. The arithmetic mean of all values is 14.1 km/h, the median is 13.8 km/h.

b) November 5th shows high correlation coefficients. Plotting the 10s–velocity (cf. Appendix A 5.1.4) reveals that there is a sudden large increase in the traffic velocity during the jam, possibly due to an incident downstream.

The correlation coefficient describes the degree that a change in one data set corresponds linearly to a change in another data set (cf. chapter 4.3). Since a large increase in the speed at both detector locations results in a high ratio between change and noise, this can explain the high correlation coefficient.

c) The correlation coefficient is generally higher further upstream. Similarly as in the previous observation, this is interpreted as a result of higher differences in the traffic speed resulting in a higher ‘change of speed’ to noise ratio. Since
these changes in speed are interpreted as due to traffic oscillations, higher correlation coefficients upstream indicate that oscillations increase in amplitude while propagating. (This interpretation is feasible, as the detectors are located equally far apart.)

d) The row labeled “overall” gives the results if the correlation between the most downstream and most upstream detector is calculated. The values range between 12.4 and 16.0 km/h and average (arithmetic mean) at 13.7 km/h.

e) The velocity for the jam on November 2 (overall: 12.9 km/h) is in the same magnitude as the one obtained in section 5.2 by the Mauch method (arithmetic mean of all waves velocities 14.2 km/h. The difference is 1.3 km/h.

Due to an arbitrary aggregation time of 10 s, only discrete velocities can be measured (cf. chapter 4.3). For the given detector spacing (500 m) and the investigated travel times, this resolution is in the range 0.8 to 1.6 km/h.

For the row labeled “overall” the resolution is between 0.2 and 0.4 km/h.

The results of the cross–correlation method suggest, that oscillations mostly generally propagate upstream at about 14 km/h upstream on the M4.

5.3.2 Cross–correlation Analysis for OR 217

Cross–correlation analysis for adjacent detectors:

The cross–correlation method is applied to data of adjacent detectors on OR 217. The results are shown in table 5-3.

Observations and interpretations:

- The measured velocities range between 15.0 and 21.0 km/h. The arithmetic mean of all measured velocities is 19.4 km/h, their median is 19.6 km/h.

- The arithmetic mean of all values for each detector pair is also given. Since it is fairly constant for all pairs, the wave speed doesn’t seem to depend on the location.

Due to an aggregation time of 20 s, only discrete velocities can be measured (cf. chapter 4.3). For the given detector spacing (about 1 km) and the investigated travel times, this resolution is in the range 1.3 to 3.0 km/h.
In order to increase this resolution, the cross–correlation method is applied to detector pairs which are located further apart in the following section.

<table>
<thead>
<tr>
<th>Detector pair</th>
<th>3.8.05 7:43 – 8:33</th>
<th>4.18.05 7:30 – 8:31</th>
<th>9.1.05 15:07 – 17:44</th>
<th>9.16.05 7:42 – 8:53</th>
<th>9.16.05 14:49 – 18:26</th>
<th>9.22.05 7:28 – 8:51</th>
<th>9.26.05 7:35 – 9:04</th>
<th>arithmetic mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 – 8</td>
<td>19.1 (0.60)</td>
<td>17.4 (0.62)</td>
<td>19.1 (0.60)</td>
<td>19.1 (0.56)</td>
<td>19.1 (0.46)</td>
<td></td>
<td></td>
<td>18.8</td>
</tr>
<tr>
<td>6 – 7</td>
<td>21.0 (0.64)</td>
<td>18.7 (0.59)</td>
<td>18.7 (0.59)</td>
<td>21.0 (0.62)</td>
<td>18.7 (0.51)</td>
<td></td>
<td></td>
<td>19.6</td>
</tr>
<tr>
<td>5 – 6</td>
<td>20.6 (0.78)</td>
<td>20.6 (0.52)</td>
<td>18.3 (0.67)</td>
<td>15.0 (0.34)</td>
<td>20.6 (0.75)</td>
<td>20.6 (0.63)</td>
<td></td>
<td>19.3</td>
</tr>
<tr>
<td>4 – 5</td>
<td>21.7 (0.77)</td>
<td>17.8 (0.50)</td>
<td>19.6 (0.50)</td>
<td>19.6 (0.58)</td>
<td>19.6 (0.63)</td>
<td>19.6 (0.66)</td>
<td>19.6 (0.51)</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Table 5-3: Velocity on OR 217, identified by cross–correlation method. Velocities are given in km/h and the numbers in brackets refer to the corresponding correlation coefficient.

**Cross–correlation Analysis for non–adjacent detectors:**

If the cross–correlation method is applied to data from detectors further apart it is not always possible to identify a clear peak of the correlation coefficient and thus a characteristic travel time. This is especially the case if the detectors are located far apart. Therefore table 5-4 gives the results of the cross–correlation method for detector pairs which are:

- close enough together that a clear peak can be identified and
- as far apart as possible.

The last row shows the average propagation velocity for the whole jam. It is calculated by

\[
\bar{u} = \frac{\sum_{i} t_{i} s_{i}}{\sum_{i} s_{i}}
\]  

(5-1)

with:

- \( \bar{u} \): average speed of oscillation,
- \( t_{i} \): travel time of oscillations for segment i and
- \( s_{i} \): length of segment i.

**Results:**

37
The average speeds range between 17.2 and 20.6 km/h with an arithmetic mean of 19.3 km/h and a median of 19.5 km/h.

The results of the cross–correlation method suggest that oscillations generally propagate upstream at about 19 – 20 km/h upstream on OR 217.

<table>
<thead>
<tr>
<th>Detector pair</th>
<th>3.8.05 7:43 – 8:33</th>
<th>4.18.05 7:30 – 8:31</th>
<th>9.1.05 5:07 – 17:44</th>
<th>9.16.05 7:42 – 8:53</th>
<th>9.16.05 14:49 – 18:26</th>
<th>9.22.05 7:28 – 8:51</th>
<th>9.26.05 7:35–9:04</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 – 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 – 7</td>
<td>19.5 (0.36)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 – 6</td>
<td></td>
<td>18.0 (0.45)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 – 5</td>
<td></td>
<td></td>
<td>19.6 (0.50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>19.5</td>
<td>18.0</td>
<td>19.6</td>
<td>20.6</td>
<td>17.2</td>
<td>19.5</td>
<td>20.6</td>
</tr>
</tbody>
</table>

Table 5-4: Results of cross–correlation method applied to non–adjacent detectors (Velocities are given in km/h, the number in brackets is the corresponding correlation coefficient)

5.3.3 Cross–correlation Analysis for A9

Table 5-5 shows the results if the cross–correlation method is applied to the data of adjacent detectors of the A 9.

<table>
<thead>
<tr>
<th></th>
<th>6.27.02 16:00 – 19:01</th>
<th>6.28.02 12:48 – 18:10</th>
<th>7.3.02 16:40 – 18:30</th>
<th>7.4.02 16:25 – 18:30</th>
<th>7.5.02 12:37 – 13:59</th>
<th>Possible velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 – 12</td>
<td></td>
<td>18.6 (0.57)</td>
<td>18.6 (0.76)</td>
<td>18.6 (0.76)</td>
<td>24.8/18.6/14.9</td>
<td></td>
</tr>
<tr>
<td>12 – 13</td>
<td>15.0 (0.60)</td>
<td>15.0 (0.66)</td>
<td>10.0 (0.50)</td>
<td>15.0 (0.72)</td>
<td>15.0 (0.68)</td>
<td>20.0/15.0/12.0/10.0</td>
</tr>
<tr>
<td>13 – 14</td>
<td>15.9 (0.55)</td>
<td></td>
<td>15.9 (0.74)</td>
<td>15.9 (0.60)</td>
<td>21.2/15.9/12.7/10.6</td>
<td></td>
</tr>
<tr>
<td>14 – 15</td>
<td>12.3 (0.78)</td>
<td></td>
<td>24.6 (0.85)</td>
<td></td>
<td>24.6/12.3/8.2</td>
<td></td>
</tr>
<tr>
<td>15 – 16</td>
<td>16.4 (0.77)</td>
<td></td>
<td>16.4 (0.82)</td>
<td></td>
<td>24.6/16.4/12.3/9.8</td>
<td></td>
</tr>
<tr>
<td>16 – 17</td>
<td>17.8 (0.61)</td>
<td></td>
<td></td>
<td></td>
<td>22.2/17.8/14.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-5: Wave velocity on A9, identified by cross–correlation method for adjacent detectors (velocities are given in km/h, the number in brackets is the corresponding correlation coefficient).
Country specific analysis of oscillating congested traffic

Since the aggregation time is fairly high (1 minute), the resolution of the identified propagation velocities is low. Therefore possible velocities are given in the table as well.

Results:

- The propagation velocity is in the range 10.0 to 24.6. The arithmetic mean of all values is 17.1 km/h, the median is 15.9 km/h.

- The resolution of the possible velocities is very low. This can be a reason for the large range.

Since the resolution of the propagation velocities that can be identified this way is very low, the cross–correlation method is applied to the first and last detector of the investigated part of the jam. The results are given in table 5-6.

<table>
<thead>
<tr>
<th>Detectors</th>
<th>6.27.02 16:00 – 19:01</th>
<th>6.28.02 12:48 – 18:10</th>
<th>7.3.02 16:40 – 18:30</th>
<th>7.4.02 16:25 – 18:30</th>
<th>7.5.02 12:37 – 13:59</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 – 12</td>
<td>16.8 (0.50)</td>
<td>10.0 (0.50)</td>
<td>17.0 (0.64)</td>
<td>16.5 (0.41)</td>
<td></td>
</tr>
<tr>
<td>12 – 13</td>
<td>17.9 (0.28)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 – 14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 – 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 – 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 – 17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-6 Velocity on A9, identified by cross–correlation method for the whole investigated part of the jam (velocities are given in km/h, the number in brackets is the corresponding correlation coefficient)

Observations:

The average propagation speeds of the jams range between 10 and 17.9 km/h. The arithmetic mean is 15.6 km/h, the median is 16.8 km/h.

This suggests that oscillations generally propagate upstream at about 16 km/h on the A9.
5.4 Cycle time by autocorrelation

In this section the autocorrelation method (cf. chapter 4.4) is applied to the data. This yields to a conclusion regarding the cycle time of traffic oscillations.

Figure 5-3 gives the autocorrelation coefficient for detector 8 (M4, Nov. 2, 1998, 18:31 – 19:31).

Observations:

- The correlation coefficient has a distinct peak for a time shift of 700 s.
- Further peaks exist for a time shift of 1460 s, 2160 s and 2840 s.
- Peaks generally exist for time shifts which are multiples of 700 s.

Interpretation of observations:

- The velocity profile measured at this detector has periodic components.
- The cycle time is about 700 s (11.7 min).
- It is assumed that this is also the cycle time of the oscillations. Oscillations therefore arise regularly about every 700 s (11.7 min).
- This interpretation is consistent with observation e) in chapter 5.2, where the time gap is identified as 10 – 13 minutes by visual inspection.

As shown, this methodology can be used to identify the cycle time of oscillations. Therefore the autocorrelation method is applied to the data of other detector locations, other jams and other sites in the following sections.
Country specific analysis of oscillating congested traffic

**Figure 5-3: Autocorrelation method applied to data from M4 (detector 8, November 2, 1998, 18:31–19:31)**

**Classification of results:**

Since the results are often not as clear as in the presented case, they are categorized in three classes. Table 5-7 gives their description.

<table>
<thead>
<tr>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>The results of the analysis are clear enough to draw conclusions.</td>
<td>The results of the analysis are not very clear. A cycle time can be identified, but requires further verification.</td>
<td>The results of the analysis are not clear enough to draw conclusions.</td>
</tr>
</tbody>
</table>

*Table 5-7: Classification of the results of the autocorrelation method*
Subjective interpretation is sometimes necessary to identify the exact time gap and then classify it. Further research is needed to find methods which do not rely on this subjective interpretation.

The following aspects have been considered in order to perform the classification:

- the distinctiveness of the peak (i.e. if a peak can clearly be identified and the correlation coefficient decreases quickly for little changes in the time shift),

- the periodicity of the autocorrelation function (i.e. the existence of further peaks located equally apart and at a multiple time shift of the first peak) and

- the value of the correlation coefficient.

The following sections show the site–specific results of the autocorrelation method.

### 5.4.1 Autocorrelation method applied to M4 Data

The autocorrelation method can be applied to other detectors and other jams on the M4. The cycle times identified in this manner and their classification can be found in table 5-8.

For illustration purposes, every value assigned class A is marked green and every value corresponding to categorization B is marked yellow.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>A 120 s C</td>
<td>B 300 s C</td>
<td>C</td>
<td>A 530 s C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>A 520 s C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td>A 730 s C</td>
<td>B 470 s C</td>
<td>C</td>
<td>A 510 s C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>6</td>
<td>A 720 s A 500 s C</td>
<td>C</td>
<td>C</td>
<td>A 460 s C</td>
<td>A 590 s C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>7</td>
<td>A 710 s A 500 s C</td>
<td>B 300 s C</td>
<td>C</td>
<td>A 480 s C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>8</td>
<td>A 700 s A 510 s C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 5-8: Results of Autocorrelation method for M4*

Table 5-9 summarizes table 5-8 by giving the range, mean and median. It shall be emphasized that any conclusion drawn from class B results needs to be verified by further research.
Table 5-9: Range, mean and median of the results of the autocorrelation method for M4

The results of the autocorrelation method suggest that oscillations can occur with a cycle time of roughly 8 – 12 minutes on the M4.

5.4.2 Autocorrelation method applied to OR 217 Data

In this section, the autocorrelation method is applied to data from OR 217. The results are given in table 5-10.

Table 5-10: Results of autocorrelation method for OR 217

Table 5-11 summarizes table 5-10 by giving the range, mean and median. It shall be emphasized that any results classified as B are based on interpretation. Therefore any conclusion drawn on their account needs to be verified by further research.
Table 5-11: Range, mean and median of the results of the autocorrelation method for OR 217

The results of the autocorrelation method suggest that oscillations can occur with a cycle time of roughly 3 – 6 minutes on OR 217.

### 5.4.3 Autocorrelation Method applied to A9 Data

Results on the autocorrelation method applied to data from the A9 are given in table 5-12.

<table>
<thead>
<tr>
<th>Detector</th>
<th>6.27.02 16:00 – 19:01</th>
<th>6.28.02 12:48 – 18:10</th>
<th>7.3.02 16:40 – 18:30</th>
<th>7.4.02 16:25 – 18:30</th>
<th>7.5.02 12:37 – 13:59</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>A 20 min</td>
<td>A 30 min</td>
<td>A 20 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>C</td>
<td>A 19 min</td>
<td>C</td>
<td>B 30 min</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>C</td>
<td>C</td>
<td>A 21 min</td>
<td>A 31 min</td>
<td>C</td>
</tr>
<tr>
<td>14</td>
<td>C</td>
<td>B 10 / 30 min</td>
<td></td>
<td>A 10 min</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>C</td>
<td>B 10 / 30 min</td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>16</td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>B 8 min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-12: Results of autocorrelation method for A9

Table 5-13 summarizes table 5-12 by giving the range, mean and median.

The results of the autocorrelation method suggest that oscillations can occur with a cycle time of roughly 10 – 30 minutes on the A9.
5.5 Spectral analysis by Fourier transformation

The previous analysis showed that oscillations can arise regularly and (to a certain degree) periodically. To further investigate their frequency, a spectral analysis is performed by use of the discrete Fourier transformation.

5.5.1 Frequency spectrum at one location

Figure 5-4 shows the frequency spectrum for velocity data of detector 8 (M4, Nov. 2, 1998, 18:31 – 19:31). (The absolute values of the Fourier coefficients are plotted in the figure.)

Observations:

a) Generally, the amplitudes of low frequencies are high whereas the values of high frequencies are low. In this particular case, amplitudes are especially high for frequencies lower than a threshold which is somewhere between 0.25 to 0.50 min\(^{-1}\).

b) The amplitude for the frequency 0 min\(^{-1}\) (static part of the signal) is very high (21.8 km/h) and is not fully shown for illustration purposes.

c) A clear peak exists for a frequency of 0.083 min\(^{-1}\).

Observations a) and b) were also made for other jams (results are not shown here).

<table>
<thead>
<tr>
<th>Class</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>10 min – 31 min (600 s – 1860 s)</td>
<td>8 min – 30 min (480 s – 1800 s)</td>
</tr>
<tr>
<td>Arithmetic mean</td>
<td>21.8 min (1310 s)</td>
<td>15.6 min / 23.6 min (936 s / 1416 s)</td>
</tr>
<tr>
<td>Median</td>
<td>20/21 min (1200 / 1260 s)</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-13: Range, mean and median of the results of the autocorrelation method for A9
Interpretations to Observations:

a) Low frequencies are interpreted as characteristic for traffic oscillations. High frequencies are interpreted as the effect of noise.

b) The high value for the static part yields the trivial conclusion that the average speed of the investigated time period is 21.8 km/h (c.f. [28]).

c) The frequency of 0.083 min⁻¹ yields a cycle time of 12.0 min. This is very close to the cycle time of 11.7 min which was obtained in section 5.4 using the autocorrelation method.

Interpretation c) supports that the autocorrelation method can be used to identify the oscillation frequency.
5.5.2 Frequency spectra for adjacent detector locations

A spectral analysis can also be performed for the data of other detector locations. Figure 5-5 shows the results for stations 7 and 8 (M4, November 2, 18:31 – 19:31). The same observations can be made as in the previous section.

(In order to highlight the spectrum which is interpreted as characteristic for traffic oscillations, it is only shown between 0 and 1 min⁻¹.)

**Figure 5-5: Spectral analysis for velocity data of detector stations 7 (downstream; green dotted line) and 8 (upstream; blue solid line) (M4, November 2, 1998, 18:31 – 19:31, 10 s aggregation)**

**Observations:**

a) The frequency spectra of both detector stations show the same pattern for low frequencies.

b) The spectra don’t match for high frequencies. A correlation doesn’t seem to exist.
c) For low frequencies amplitude (i.e. the absolute value of the Fourier coefficient) is higher at upstream location than downstream.

Interpretations to observations:

a) Low frequencies are characteristic for traffic oscillations (cf. interpretation a) in previous section). Since oscillations propagate through the network, the spectra of both detector locations match for low frequencies.

b) By definition (cf. chapter 2.1.2), oscillations propagate through the freeway network. Since high frequencies are not found upstream in the same pattern as they are downstream, they are unlikely due to traffic oscillations. This supports interpretation a) in the previous section referring to them as noise.

c) This complies with the finding that oscillations grow in amplitude while propagating upstream (cf. chapter 2.3.1).

The results support the interpretation that traffic oscillations are characterized by the low frequencies in the velocity’s frequency spectrum.
Chapter 6 Conclusion and Outlook

6.1 Comparison of results and their interpretation

This thesis aims at a country specific comparison of traffic oscillations. Towards this end, analysis was performed regarding their propagation speed and frequency. The results are now summarized and conclusion on general differences between countries is drawn.

6.1.1 Propagation speed of oscillations

The results of the analysis are given in the following table.

<table>
<thead>
<tr>
<th></th>
<th>M4</th>
<th>OR 217</th>
<th>A9</th>
</tr>
</thead>
<tbody>
<tr>
<td>(UK)</td>
<td>14 km/h</td>
<td>19 – 20 km/h</td>
<td>16 km/h</td>
</tr>
<tr>
<td>(USA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Germany)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 6-1: Average propagation speed*

- The results are of the same magnitude as those found in the literature (cf. chapter 2.3.2). They support the hypothesis that oscillations propagate upstream with a higher velocity in the USA than they do in Germany.
- The analysis also shows that traffic oscillations propagate more slowly on the M4 than in the other two countries. Since no studies on other sites in the UK were found, further research should verify whether this finding can be generalized.

### 6.1.2 Frequency of oscillations

The magnitude of the cycle times obtained by the autocorrelation method is given in the following table.

<table>
<thead>
<tr>
<th></th>
<th>M4 (UK)</th>
<th>OR 217 (USA)</th>
<th>A9 (Germany)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>8 – 12 min</td>
<td>3 – 6 min</td>
<td>10 – 30 min</td>
</tr>
</tbody>
</table>

*Table 6-2: Magnitude of cycle times identified in this study*

Even though the results were not always clear, they indicate that traffic oscillation appear with a frequency on OR 217 which is considerably higher than on the A9.

Different sites are likely to show different frequencies (cf. chapter 2.3.3). Hence, results obtained at one location only cannot be generalized.

The literature review also showed oscillation frequencies of similar range for other American and other German sites. This indicates that a general difference in the oscillation frequency between German and American Highways exist. However, the results were not always clear. Therefore further research should verify this possible finding.

If the frequency of oscillations in the USA is higher than in Germany, the following general conclusions can be made. They are explained in figure 6-1:

1. Amplitudes of oscillations are usually higher in Germany than in the USA

2. Oscillations are usually more distinct in Germany than they are in the USA, i.e. they are easier to detect.

(The second conclusion might explain a supposition mentioned by Dr. Martin Treiber, that oscillating traffic conditions are less common in the USA than in Germany.)
Figure 6-1: Conclusions if country specific difference in frequency exists

6.2 Outlook

This thesis suggests a difference in the frequency of traffic oscillations between Germany and the USA. For verification, the following research can be pursued:

- The frequency of traffic oscillations is likely site specific (cf. figure 2-6). Hence, analysis of different locations should verify a general difference.

- In this thesis, the cycle time is identified by using subjective interpretation. Therefore the applied method should be improved. A possible approach is given in [14] where the power density spectrum (i.e. the Fourier transformation of the autocorrelation function) is calculated. Preliminary analysis show good results of this method.
A direct analysis of the amplitude was not performed in this thesis since it is dependent on ramp flows (cf. chapter 2.3.1). As a comparison would be interesting, freeway sections without ramps (such as on the M4) can be analyzed in order to identify country specific differences.

If the hypothesis can be verified, that the oscillation frequency is considerably higher in the USA than in Germany, then further research can identify the causes for this difference. Simulation and analysis of car–following models might reveal the impact on the cycle time of various influence factors (e.g. reaction time and sensitivity). Conclusions on country specific differences of these factors might be possible in the future. It is possible that the difference in propagation speed is due to the same influence factors as the difference in frequency (if a difference in frequency exists). Therefore the effects of these influence factors on the propagation speed should also be analyzed.
References


[18] http://portal.its.pdx.edu (Data available on the attached CD)

[19] https://keiko.odot.state.or.us/whalecome625540f33e0118833db435ae262/whalecom0/SecureKeikoPortalHomePage/ (Respective images are available on the attached CD)


[27] Heinz, G.: Mittelwert, Korrelation, Faltung


Declaration of authorship

Selbständigkeitsklärung:

Hierdurch erkläre ich, dass ich die von mir am heutigen Tage eingereichte Diplomarbeit selbständig verfasst und andere als die angegebenen Hilfsmittel nicht benutzt habe.


(Benjamin A. Zielke)
A Appendix

A 1 Merging of congested flows

Two congested flows merge at a constant ratio $\alpha$, i.e.:

\[
\alpha = \frac{q_{up}}{q_{on}}
\]

$\iff q_{up} = \alpha \cdot q_{on}$

$\iff q_{up} = \alpha (q_{down} - q_{up})$ (since $q_{on} = q_{down} - q_{up}$)

$\iff q_{up} + \alpha q_{up} = \alpha q_{down}$

$\iff q_{down} = \frac{1 + \alpha}{\alpha} q_{up}.$

$q_{down}$: flow downstream of ramp

$q_{on}$: onramp flow

$q_{up}$: flow upstream of ramp
A 2 Numbering of detector locations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>unknown</td>
<td>1</td>
</tr>
<tr>
<td>0.45</td>
<td>0.315</td>
<td>2</td>
</tr>
<tr>
<td>0.76</td>
<td>1.01</td>
<td>3</td>
</tr>
<tr>
<td>1.92</td>
<td>1.90</td>
<td>4</td>
</tr>
<tr>
<td>2.55</td>
<td>2.575</td>
<td>5</td>
</tr>
<tr>
<td>3.12</td>
<td>3.145</td>
<td>6</td>
</tr>
<tr>
<td>3.5</td>
<td>3.725</td>
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<tr>
<td>4.35</td>
<td>4.385</td>
<td>8</td>
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<td>5.11</td>
<td>5.05</td>
<td>9</td>
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<tr>
<td>5.95</td>
<td>6.05</td>
<td>10</td>
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<tr>
<td>6.77</td>
<td>6.835</td>
<td>11</td>
</tr>
<tr>
<td>7.00</td>
<td>7.08</td>
<td>12</td>
</tr>
</tbody>
</table>

*Table A-1: Labeling of detector locations on OR 217*

<table>
<thead>
<tr>
<th>Detector location [km]</th>
<th>original labeling</th>
<th>new labeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>512.29</td>
<td>160</td>
<td>1</td>
</tr>
<tr>
<td>513.28</td>
<td>250</td>
<td>2</td>
</tr>
<tr>
<td>514.17</td>
<td>260</td>
<td>3</td>
</tr>
<tr>
<td>515.332</td>
<td>280</td>
<td>4</td>
</tr>
<tr>
<td>516.1</td>
<td>290</td>
<td>5</td>
</tr>
<tr>
<td>517.49</td>
<td>300</td>
<td>6</td>
</tr>
<tr>
<td>518.97</td>
<td>320</td>
<td>7</td>
</tr>
<tr>
<td>519.78</td>
<td>340</td>
<td>8</td>
</tr>
<tr>
<td>520.78</td>
<td>350</td>
<td>9</td>
</tr>
<tr>
<td>521.49</td>
<td>380</td>
<td>10</td>
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<tr>
<td>522.14</td>
<td>390</td>
<td>11</td>
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<td>420</td>
<td>12</td>
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<tr>
<td>524.38</td>
<td>540</td>
<td>13</td>
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<tr>
<td>525.44</td>
<td>560</td>
<td>14</td>
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<tr>
<td>525.85</td>
<td>580</td>
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<td>526.67</td>
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<tr>
<td>528.15</td>
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</tbody>
</table>

*Table A-2: Labeling of detector locations for A9*
### Detector location

<table>
<thead>
<tr>
<th>Detector location [km]</th>
<th>original labeling</th>
<th>new labeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.2</td>
<td>162</td>
<td>1</td>
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<tr>
<td>16.7</td>
<td>167</td>
<td>2</td>
</tr>
<tr>
<td>17.2</td>
<td>172</td>
<td>3</td>
</tr>
<tr>
<td>17.7</td>
<td>177</td>
<td>4</td>
</tr>
<tr>
<td>18.2</td>
<td>182</td>
<td>5</td>
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<tr>
<td>18.7</td>
<td>187</td>
<td>6</td>
</tr>
<tr>
<td>19.3</td>
<td>193</td>
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<tr>
<td>19.7</td>
<td>197</td>
<td>8</td>
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<td>20.5</td>
<td>205</td>
<td>9</td>
</tr>
<tr>
<td>21.1</td>
<td>211</td>
<td>10</td>
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<tr>
<td>21.6</td>
<td>216</td>
<td>11</td>
</tr>
<tr>
<td>22.1</td>
<td>221</td>
<td>12</td>
</tr>
<tr>
<td>23.2</td>
<td>232</td>
<td>13</td>
</tr>
</tbody>
</table>

*Table A-3: Labeling of detector locations for M4*

### A 3 Mathematical transformation – Mauch method

\[
D(t) = S(t) - \frac{S(t-\tau) + S(t+\tau)}{2} \frac{1}{S_r(t)}
\]

\[
D(t) = \int_{t_0}^{t} v(t')dt' - \frac{1}{2} \left( \int_{t_0}^{t-\tau} v(t')dt' + \int_{t_0}^{t+\tau} v(t')dt' \right)
\]

\[
D(t) = \int_{t_0}^{t} v(t')dt' + \int_{t_0}^{t} v(t')dt' - \frac{1}{2} \left( \int_{t_0}^{t-\tau} v(t')dt' + \int_{t_0}^{t+\tau} v(t')dt' + \int_{t_0}^{t-\tau} v(t')dt' + \int_{t_0}^{t+\tau} v(t')dt' \right)
\]

\[
D(t) = \int_{t_0}^{t} v(t')dt' - \frac{1}{2} \int_{t_0}^{t} v(t')dt'
\]

\[
D(t) = \frac{1}{2} \int_{t_0}^{t} v(t')dt' - \frac{1}{2} \int_{t_0}^{t} v(t')dt'
\]

\[
D(t) \sim \int_{t_0}^{t} v(t')dt' - \int_{t_0}^{t} v(t')dt'
\]
A 4 Velocity plots

A 4.1 Velocity plots for M4

Figure 2: M4 – November 2, 1998

Figure 3: M4 – November 3, 1998
Figure 4: November 4, 1998

Figure 5: November 5, 1998
Country specific analysis of oscillating congested traffic

Figure 6: November 9, 1998

Figure 7: November 10, 1998
Country specific analysis of oscillating congested traffic

Figure 8: November, 11, 1998

A 4.2 Velocity plots for OR 217

Figure 9: March 8, 2005
Country specific analysis of oscillating congested traffic

**Figure 10:** April 18, 2005

**Figure 11:** September 1, 2005
Country specific analysis of oscillating congested traffic

Figure 12: September 16, 2005

Figure 13: September 22, 2005
Figure 14: September 26, 2005

A 4.3 Velocity plots for A9

Figure 15: June 27, 2002
Country specific analysis of oscillating congested traffic

Figure 16: June 28, 2002

Figure 17: July 3, 2002
Country specific analysis of oscillating congested traffic

Figure 18: July 4, 2002

Figure 19: July 5, 2002
A 5  Velocity

A 5.1 Velocity for M4

A 5.1.1 Velocity for M4, November 2, 1998, 18:31 – 19:31

Figure 20: Detector 3

Figure 21: Detector 4

Figure 22: Detector 5

Figure 23: Detector 6

Figure 24: Detector 7

Figure 25: Detector 8
A 5.1.2 Velocity for M4, November 3, 1998, 7:11 – 7:58

Figure 26: Detector 3

Figure 27: Detector 4

Figure 28: Detector 5

Figure 29: Detector 6

Figure 30: Detector 7
A 5.1.3 Velocity for M4, November 4, 1998, 7:14 – 8:20

Figure 31: Detector 3

Figure 32: Detector 4

Figure 33: Detector 5

Figure 34: Detector 6

Figure 35: Detector 7
A 5.1.4 Velocity for M4, November 5, 1998, 8:51 – 9:59

Figure 36: Detector 3

Figure 37: Detector 4

Figure 38: Detector 5

Figure 39: Detector 6

Figure 40: Detector 7
A 5.1.5 Velocity for M4, November 9, 1998, 7:16 – 8:04

Figure 41: Detector 3

Figure 42: Detector 4

Figure 43: Detector 5

Figure 44: Detector 6

Figure 45: Detector 7
Country specific analysis of oscillating congested traffic

A 5.1.6 Velocity for M4, November 10, 1998, 7:03 – 8:15

Figure 46: Detector 3

Figure 47: Detector 4

Figure 48: Detector 5

Figure 49: Detector 6

Figure 50: Detector 7
Country specific analysis of oscillating congested traffic

A 5.1.7 Velocity for M4, November 11, 1998, 7:11 – 8:11

Figure 51: Detector 3

Figure 52: Detector 4

Figure 53: Detector 5

Figure 54: Detector 6

Figure 55: Detector 7
A 5.2 Velocity for OR 217

A 5.2.1 Velocity for OR 217, March 8, 2005, 7:43 – 8:33

Figure 56: Detector 4

Figure 57: Detector 5

Figure 58: Detector 6

Figure 59: Detector 7

Figure 60: Detector 8
A 5.2.2 Velocity for OR 217, April 18, 2005, 7:30 – 15:31

Figure 61: Detector 4

Figure 62: Detector 5

Figure 63: Detector 6

Figure 64: Detector 7

Figure 65: Detector 8
A 5.2.3 Velocity for OR 217, September 1, 2005, 15:07 – 17:44

Figure 66: Detector 4

Figure 67: Detector 5

Figure 68: Detector 6

A 5.2.4 Velocity for OR 217, September 16, 2005, 7:42 – 8:53

Figure 69: Detector 4

Figure 70: Detector 5
Figure 71: Detector 6

Figure 72: Detector 7

Figure 73: Detector 8
A 5.2.5 Velocity for OR 217, September 16, 2005, 14:49 – 18:26

Figure 74: Detector 4

Figure 75: Detector 5

A 5.2.6 Velocity for OR 217, September 22, 2005, 7:28 – 8:51

Figure 77: Detector 4

Figure 78: Detector 5
A 5.2.7 Velocity for OR 217, September 26, 2005, 7:35 – 9:04
Country specific analysis of oscillating congested traffic

Figure 84: Detector 6

Figure 85: Detector 7

Figure 86: Detector

A 5.3 Velocity for A9

A 5.3.1 Velocity for June 27, 2002, 16:00 – 19:01

Figure 87: Detector 12

Figure 88: Detector 13
Country specific analysis of oscillating congested traffic

A 5.3.2 Velocity for June 28, 2002, 12:48 – 18:10
84

Country specific analysis of oscillating congested traffic

Figure 95: Detector 13

A 5.3.3 Velocity for July 3, 2002, 16:40 – 18:30

Figure 96: Detector 12

Figure 97: Detector 13

A 5.3.4 Velocity for July 4, 2002, 16:25 – 18:30

Figure 98: Detector 11

Figure 99: Detector 12
A 5.3.5 Velocity for July 5, 2002, 12:37 – 13:59

Figure 100: Detector 13

Figure 102: Detector 15

Figure 101: Detector 14

Figure 103: Detector 16

Figure 104: Detector 11

Figure 105: Detector 12
Country specific analysis of oscillating congested traffic

Figure 106: Detector 13

Figure 107: Detector 14
A 6 Mauch method

A 6.1 Mauch method for M4

Figure 108: Mauch method for Detectors 3 to 8 on M4, November 2, 18:38 – 19:24
Figure 109: Mauch method for Detectors 3 to 8 on M4, November 3, 7:18 – 7:51

Figure 110: Mauch method for Detectors 3 to 7 on M4, November 4, 7:21 – 8:13
Figure 111: Mauch method for Detectors 3 to 7 on M4, November 5, 8:58 – 9:49

Figure 112: Mauch method for Detectors 3 to 7 on M4, November 9, 7:23 – 7:57
Country specific analysis of oscillating congested traffic

Figure 113: Mauch method for Detectors 3 to 7 on M4, November 10, 7:10 – 8:08

Figure 114: Mauch method for Detectors 3 to 7 on M4, November 11, 7:18 – 8:04
A 6.2 Mauch method for OR 217

Figure 115: Mauch method for OR 217, March 8, 2005, 7:50 – 8:26, Detectors 4 – 8

Figure 116: Mauch method for OR 217, April 18, 7:37 – 8:24, Detectors 4 – 8
Country specific analysis of oscillating congested traffic

Figure 117: Mauch method for OR 217, September 1, 2005, 15:14 – 17:37, Detectors 4 – 5

Figure 118: Mauch method for OR 217, September 16, 2005, 7:49 – 8:48, Detectors 4 – 8
Country specific analysis of oscillating congested traffic

**Figure 119**: Mauch method for OR 217, September 16, 2005, 14:56 – 18:26, Detectors 4 – 6

**Figure 120**: Mauch method for OR 217, September 22, 2995, 7:35 – 8:44, Detectors 4 – 8
Figure 121: Mauch method for OR 217, September 26, 2005, 7:42 – 8:57, Detectors 4 – 8
A 6.3 Mauch method for A9

Figure 122: Mauch method for A9, June 27, 2002, 16:07 – 18:54, detectors 12 – 17

Figure 123: Mauch method for A9, June 28, 2002, 12:55 – 18:03, detectors 11 – 13
Figure 124: Mauch method for A9, July 3, 2002, 16:47 – 18:23, detectors 12 and 13

Figure 125: Mauch method for A9, July 4, 2002, 16:32 – 18:23, detectors 12 – 16
Country specific analysis of oscillating congested traffic

*Figure 126: Mauch method for A9, July 5, 2002 12:44 – 13:52, detectors 11 – 14*
A 7 Cross–correlation method

A 7.1 Cross–correlation Coefficient for M4


Figure 127: Detectors 3 and 4

Figure 128: Detector 4 and 5

Figure 129: Detectors 5 and 6

Figure 130: Detectors 6 and 7

Figure 131: Detectors 7 and 8

Figure 132: Detectors 3 and 8

Figure 133: Detectors 3 and 4

Figure 134: Detectors 4 and 5

Figure 135: Detectors 5 and 6

Figure 136: Detectors 6 and 7

Figure 137: Detectors 3 and 7

Figure 138: Detectors 3 and 4

Figure 139: Detectors 4 and 5

Figure 140: Detectors 5 and 6

Figure 141: Detectors 6 and 7

Figure 142: Detectors 3 and 7

Figure 143: Detectors 3 and 4

A 7.1.5 Cross–correlation – November 9, 1998, 7:16 – 8:04

Figure 144: Detectors 3 and 4

Figure 145: Detectors 4 and 5

Figure 146: Detectors 5 and 6
Country specific analysis of oscillating congested traffic


Figure 147: Detectors 6 and 7

Figure 148: Detectors 3 and 7

Figure 149: Detectors 3 and 4

Figure 151: Detectors 5 and 6

Figure 150: Detectors 4 and 5

Figure 152: Detectors 6 and 7
Country specific analysis of oscillating congested traffic

Figure 153: Detectors 3 and 7

A 7.1.7 Cross–correlation – November 11, 1998, 7:11 – 8:11

Figure 154: Detectors 3 and 4

Figure 156: Detectors 5 and 6

Figure 155: Detectors 4 and 5

Figure 157: Detectors 6 and 7
Country specific analysis of oscillating congested traffic

Figure 158: Detectors 3 and 7
A 7.2 Cross–correlation Coefficient for OR 217

A 7.2.1 Cross–correlation – March 8, 2005, 7:43 – 8:33

Figure 159: Detectors 7 and 8

Figure 160: Detectors 6 and 7

Figure 161: Detectors 5 and 6

Figure 162: Detectors 4 and 5

Figure 163: Detectors 4 and 8
A 7.2.2 Cross-correlation – April 18, 2005, 7:30 – 8:31

Figure 164: Detectors 7 and 8
Figure 165: Detectors 6 and 7
Figure 166: Detectors 5 and 6
Figure 167: Detectors 4 and 5
Figure 168: Detectors 6 and 8
Figure 169: Detectors 4 and 6
A 7.2.3 Cross–correlation – September 1, 2005, 15:07 – 17:44

Figure 170: Detectors 4 and 5

A 7.2.4 Cross–correlation – September 16, 2005, 7:42 – 8:53

Figure 171: Detectors 7 and 8
Figure 173: Detectors 5 and 6

Figure 172: Detectors 6 and 7
Figure 174: Detectors 4 and 5
Figure 175: Detectors 6 and 8

Figure 176: Detectors 4 and 6

A 7.2.5 Cross–correlation – September 16, 2005, 14:49 – 18:26

Figure 177: Detectors 5 and 6

Figure 178: Detectors 4 and 5

A 7.2.6 Cross–correlation – September 22, 2005, 7:28 – 8:51

Figure 179: Detectors 7 and 8

Figure 180: Detectors 6 and 7
Country specific analysis of oscillating congested traffic

Figure 181: Detectors 5 and 6

Figure 182: Detectors 4 and 5

A 7.2.7 Cross–correlation – September 26, 2005, 7:35 – 9:04

Figure 183: Detectors 7 and 8

Figure 185: Detectors 5 and 6

Figure 184: Detectors 6 and 7

Figure 186: Detectors 4 and 5
Country specific analysis of oscillating congested traffic

A 7.3 Cross–correlation for A9

A 7.3.1 Cross–correlation – June 27, 2002, 16:00 – 19:01

Figure 187: Detectors 4 and 8

Figure 188: Detectors 12 and 13

Figure 189: Detectors 13 and 14

Figure 190: Detectors 14 and 15

Figure 191: Detectors 15 and 16
Country specific analysis of oscillating congested traffic

Figure 192: Detectors 16 and 17

Figure 193: Detectors 12 and 17


Figure 194: Detectors 11 and 12

Figure 196: Detectors 11 and 13

Figure 195: Detectors 12 and 13
A 7.3.3 Cross–correlation – July 3, 2002, 16:40 – 18:30

Figure 197: Detectors 12 and 13

A 7.3.4 Cross–correlation – July 4, 2002, 16:25 – 18:30

Figure 198: Detectors 11 and 12

Figure 200: Detectors 13 and 14

Figure 199: Detectors 12 and 13

Figure 201: Detectors 14 and 15
Country specific analysis of oscillating congested traffic


Figure 202: Detectors 15 and 16

Figure 203: Detectors 11 and 16

Figure 204: Detectors 11 and 12

Figure 205: Detectors 12 and 13

Figure 206: Detectors 13 and 14

Figure 207: Detectors 11 and 14
A 8 Autocorrelation method

A 8.1 Autocorrelation Coefficient for M4

A 8.1.1 Autocorrelation for M4, November 2, 1998, 18:31 – 19:31

Figure 208: Detector 3

Figure 209: Detector 4

Figure 210: Detector 5

Figure 211: Detector 6

Figure 212: Detector 7

Figure 213: Detector 8

Figure 214: Detector 3

Figure 215: Detector 4

Figure 216: Detector 5

Figure 217: Detector 6

Figure 218: Detector 7

Figure 219: Detector 8

Figure 220: Detector 3

Figure 221: Detector 4

Figure 222: Detector 5

Figure 223: Detector 6

Figure 224: Detector 7
A 8.1.4 Autocorrelation for M4, November 5, 1998, 8:51 – 9:59

Figure 225: Detector 3

Figure 226: Detector 4

Figure 227: Detector 5

Figure 228: Detector 6

Figure 229: Detector 7
A 8.1.5 Autocorrelation for M4, November 9, 1998, 7:16 – 8:04

Figure 230: Detector 3

Figure 231: Detector 4

Figure 232: Detector 5

Figure 233: Detector 6

Figure 234: Detector 7
A 8.1.6 Autocorrelation for M4, November 10, 1998, 7:03 – 8:15

Figure 235: Detector 3

Figure 236: Detector 4

Figure 237: Detector 5

Figure 238: Detector 6

Figure 239: Detector 7
A 8.1.7 Autocorrelation for M4, November 11, 1998, 7:11 – 8:11

Figure 240: Detector 3

Figure 241: Detector 4

Figure 242: Detector 5

Figure 243: Detector 6

Figure 244: Detector 7
A 8.2 Autocorrelation Coefficient for OR 217

A 8.2.1 Autocorrelation for OR 217, March 8, 2005, 7:43 – 8:33

Figure 245: Detector 8

Figure 246: Detector 7

Figure 247: Detector 6

Figure 248: Detector 5

Figure 249: Detector 4
Country specific analysis of oscillating congested traffic

A 8.2.2 Autocorrelation for OR 217, April 18, 2005, 7:30 – 15:31

Figure 250: Detector 8

Figure 251: Detector 7

Figure 252: Detector 6

Figure 253: Detector 5

Figure 254: Detector 4
Country specific analysis of oscillating congested traffic

A 8.2.3 Autocorrelation for OR 217, September 1, 2005, 15:07 – 17:44

Figure 255: Detector 5

Figure 256: Detector 4

A 8.2.4 Autocorrelation for OR 217, September 16, 2005, 7:42 – 8:53

Figure 257: Detector 8

Figure 259: Detector 6

Figure 258: Detector 7

Figure 260: Detector 5
Figure 261: Detector 4

A 8.2.5 Autocorrelation for OR 217, September 16, 2005, 14:49 – 18:26

Figure 262: Detector 6

Figure 263: Detector 5

Figure 264: Detector 4
A 8.2.6 Autocorrelation for OR 217, September 22, 2005, 7:28 – 8:51

Figure 265: Detector 8

Figure 266: Detector 7

Figure 267: Detector 6

Figure 268: Detector 5

Figure 269: Detector 4
Country specific analysis of oscillating congested traffic

8.2.7 Autocorrelation for OR 217, September 26, 2005, 7:35 – 9:04

Figure 270: Detector 8

Figure 271: Detector 7

Figure 272: Detector 6

Figure 273: Detector 5

Figure 274: Detector 4
A 8.3 Autocorrelation for A9

A 8.3.1 Autocorrelation – June 27, 2002, 16:00 – 19:01

Figure 275: Detector 12

Figure 276: Detector 13

Figure 277: Detector 14

Figure 278: Detector 15

Figure 279: Detector 16

Figure 280: Detector 17

Figure 281: Detector 11

Figure 283: Detector 13

Figure 282: Detector 12

A 8.3.3 Autocorrelation – July 3, 2002, 16:40 – 18:30

Figure 284: Detector 12

Figure 285: Detector 13
Country specific analysis of oscillating congested traffic

A 8.3.4 Autocorrelation – July 4, 2002, 16:25 – 18:30

Figure 286: Detector 11  Figure 289: Detector 14

Figure 287: Detector 12  Figure 290: Detector 15

Figure 288: Detector 13  Figure 291: Detector 16

Figure 292: Detector 11

Figure 293: Detector 12

Figure 294: Detector 13

Figure 295: Detector 14

Figure 296: Detector 15