

Empirical Measurement of Freeway Oscillation Characteristics: An International Comparison

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Abstract. The objective of this paper is to conduct a country specific analysis of freeway traffic oscillations. Toward this end, loop detector data from sites in the United States, Germany and the United Kingdom 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 US, 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 US than in Germany. Furthermore, an oscillation frequency was identified by calculation of the data's autocorrelation. However, since the oscillation frequency is likely to be site specific, conclusions regarding general differences between the frequencies measured in different countries cannot yet be made. For the sites analyzed, it was found that oscillations appear every 8–12 min on the M4 (UK site), 10–30 minutes on the A9 (German site) and every 3–6 minutes on OR 217 (US site). Even though the magnitudes of the latter two countries are supported by the literature, further empirical research on several different sites should be pursued in order to draw final conclusions.

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 (e.g. ramp metering, travel time estimation, traffic state prediction, adaptive cruise control) are the focus. Since their development and deployment requires a thorough understanding of traffic flow phenomena, research has been performed resulting in various traffic models. One of them is the Lighthill Whitham Richards (LWR) model. The LWR model 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 oscillations can grow in amplitude while propagating upstream, a feature 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 completely 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 traffic oscillations might help resolve 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 exhibit different characteristics. Since traffic models aim at describing the traffic flow features, country specific differences might require different calibration of the traffic models. They might even require the use of different models. Since it is not yet clear whether traffic flow features differ from country to country, it is still uncertain whether models developed in one country can be adapted for use in another country. Therefore this paper is a first step toward identifying country-specific differences in traffic flow. More detailed information on this research is available (3). Therefore interested readers are encouraged to contact the authors for further information.

BACKGROUND

A traffic oscillation is usually defined as stop-and-go or slow-and-go conditions. For this paper, a pattern in traffic flow will be referred to as a traffic oscillation if three conditions hold:

- The space–mean speed measured on a short freeway section drops, rises and drops again over time. More information is available in (1, 4) including a definition of space–mean speed, also referred to as traffic speed in this paper.
- The traffic is congested. More information is available in (5) about the definition of congestion, also referred to as jammed or queued traffic in this paper.
- The observed pattern propagates upstream against the direction of travel.

In addition, for this paper, the amplitude of an oscillation will be defined as one half of the difference between the maximum observed speed and the minimum observed speed: $\frac{1}{2}(v_{\max} - v_{\min})$.

Causes of Oscillations

Previous research has investigated possible reasons for traffic oscillations. Two related explanations are presented in the available literature that describe the possible origin of traffic oscillations. Some researchers have tried to explain traffic oscillations due to car-following behavior. In this regard, microscopic car-following models are often used to explain traffic oscillations (4, 6, 7, 8). Using those models, oscillations form just upstream of a bottleneck and increase in amplitude due to drivers' large reaction times and their overreactions while they are propagating against the direction of travel. Other related research shows that traffic oscillations are caused by lane changing. In (9) 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. More empirical research is needed to build on and verify these findings on an array of facilities.

Characteristics of Traffic Oscillations

Previous research and this paper will consider three main characteristics of traffic oscillations that are relevant for empirical measurements and also for modeling purposes:

- Amplitude
- Propagation velocity
- Frequency

The first feature to be considered is the amplitude of oscillations in freeway traffic. When considering the amplitude of oscillations previous research has also attempted to determine conclusively whether oscillations grow or shrink in amplitude as they travel through the traffic stream. Car-following models (4, 6, 7, 8) and some empirical observations (9) have shown that oscillations do increase in amplitude while propagating upstream. (In (9) 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.)

Real freeways are heterogeneous with changes in cross-section, merges and diverges. If it is assumed that oscillations can increase in amplitude, it is possible to examine possible effects of on- and off-ramps on the amplitude of oscillations. In (9) it is found that on-ramps do have an effect on the amplitude of traffic oscillation by a "pumping effect." As a result, it was shown that oscillations do decrease in amplitude when propagating upstream past on-ramps. Similarly, it can be assumed that oscillations may increase in amplitude when passing off-ramps. However, no validation has been performed for the latter case in (9), and further empirical research is needed in this area.

A second feature to be considered is the longitudinal propagation velocity of oscillations in freeway traffic. Since oscillations are perturbations in the flow of congested traffic, various studies (2, 5, 9, 10, 11, 13, 14, 15) have suggested that they travel upstream at a characteristic velocity of about 16 km/h in Germany and about 20 km/h in the United States. Some past analysis of lateral propagation of oscillations has shown that oscillations appear in adjacent lanes shortly after they were first detected (9).

The third feature to be measured is the frequency of oscillations. It has been shown that oscillations often occur regularly (2). Therefore they can be characterized by their frequency; its reciprocal value will be referred to as period. Table 1 shows the results of a literature review on the oscillation period.

TABLE 1 Oscillation Period of Traffic Oscillations According to Literature

Study	Period (min)	Study site	Data Year	Comment
(13)	3	US (Holland Tunnel)	NA	Frequency directly upstream of the bottleneck (high frequencies might fade out upstream as explained in the text)
(9)	4-8	US (I-80)	2003	Frequency analysis was not object of analysis. Results were obtained by looking at the plots
(15)	4	US (J.C. Lodge Freeway)	1966	None

(12)	6–8	Canada (Queen Elizabeth Way)	1998	Frequency analysis was not object of analysis. Results were obtained by looking at the plots
(10)	ca. 20	Germany (A5)	2001	Frequency analysis was not object of analysis. Results were obtained by looking at the plots
(7)	5.5/7.5/15/16	Germany (A5)	NA	Oscillations were not chosen arbitrarily, They were chosen to demonstrate the effect of different periods on the amplitude, hence they might not show typical values

In (9, 10, 12) a frequency analysis was not objective 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 later). Further, according to (2), the oscillation period is dependent on flow. It has also been reported that oscillations do not exist in very low traffic flow conditions (2, 12). Since flow is restricted by site-specific bottlenecks, different sites are expected to show different characteristic oscillation frequencies. The final observation regarding frequency comes from a car-following model described in (16). The model reveals that oscillations with small frequencies would fade out whereas those with low frequencies would grow in amplitude as they propagate upstream.

One final issue relating two oscillation features has been addressed in previous research. A relation between amplitude and frequency is described in (7). That publication states that long periods are accompanied by large oscillation amplitudes, and high frequencies result in low amplitudes.

Maximum Flow Reported by Capacity Manuals

The idea of comparing traffic features between countries is not new and has led to interesting results in the past. In the context of freeway capacity, The US Highway Capacity Manual (HCM) (17) serves as a guide for the design and operation of transportation facilities and infrastructure in the US and other countries. The “Handbuch für die Bemessung von Straßenverkehrsanlagen” (HBS) (18) is the German equivalent of the HCM. Both manuals use level of service (LOS) concepts to quantify how well a facility is operating. A comparison for freeway traffic with a truck percentage of 10% has been performed (22) and has found that the thresholds for the same LOS are associated with higher per lane flows in the HCM than in the HBS. In addition, the maximum per lane flow (threshold for transition from LOS E to LOS F) is higher in the HCM than in the HBS.

Hence, a comparison of the manuals indicates that the assumed capacity of a US freeway may be higher than that of a German Autobahn. It is not clear precisely how the LOS thresholds have been determined and if they really refer to the same quality standard. Therefore further site-specific research is needed to verify whether a difference in capacity really exists.

DESCRIPTION OF THE DATA

In order to draw comparisons between reproducible characteristics of traffic oscillations, freeway loop detector data from three sites was analyzed for this study. Data was available from sites in the US, Germany, and the UK. The main characteristics of the data are summarized below and site maps are presented in Figure 1.

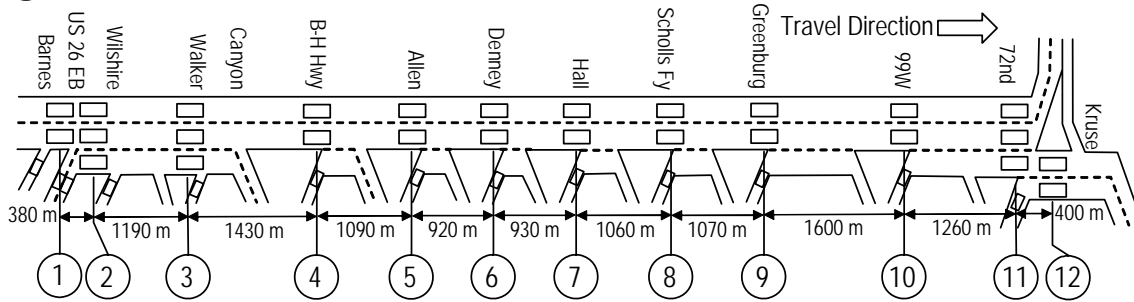
The US site is located on OR 217, a freeway southwest of Portland, Oregon. Data (velocity, count and occupancy) was available for the whole section (11.2 km) in 20 s aggregates. The data includes all freeway lanes and on-ramps. Sensors on off-ramps were not installed. The data was available for download from PORTAL (19), an online data archive for the Portland metropolitan area (data in PORTAL is provided by the Oregon Department of Transportation). Analysis was done for the southbound direction for six days in March, April and September, 2005.

The PORTAL 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. 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 (since 2006 it has been operating on a systemwide adaptive basis).

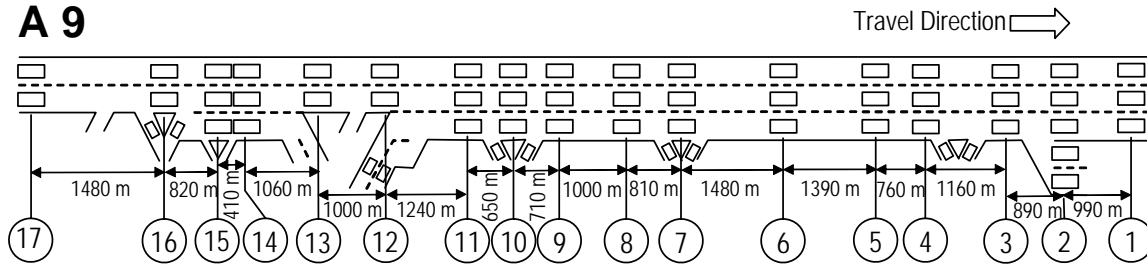
The German site is located on northbound Autobahn A9 north of Munich. Data (velocity and count) from the A9 was available from double loop detectors between km 528.2 and km 513.3 in one minute aggregates and was provided by the Autobahndirektion Südbayern. Five days in June and July, 2002 were analyzed for this study. These data are available by lane, are segregated by autos and trucks, and are available on most on- and off-ramps as shown in Figure 1. The freeway is equipped with variable message signs, a variable speed limit system and no ramp meters.

The UK site is an eastbound motorway M4 near London. Data from double loop detectors was available for the section between km 23.2 and km 16.2 for seven days in November 1998 and was provided by the UK Highways Agency and the Transport Research Laboratory. The data consist of individual vehicle arrival times and velocities for each lane. There were no ramps on the motorway, and data were collected before a bus lane was installed at the site. For the M4 data, since the analysis pursued is based on a macroscopic approach, aggregation was necessary. It was done arbitrarily for 10 s intervals.

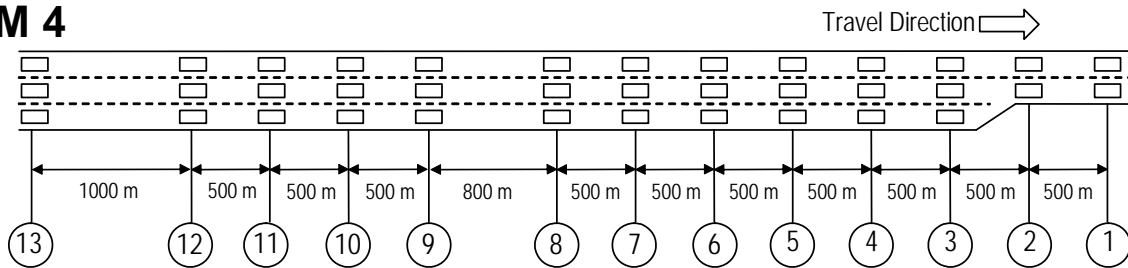
OR 217



A 9



M 4



□ Loop detector station

FIGURE 1 Site maps for OR 217 (US), A9 (Germany) and M4 (UK).

METHODOLOGY

Since traffic data is generally noisy, it is difficult to identify specific characteristics by simply plotting the raw data over time. Therefore this paper applies three basic methods to analyze and compare oscillation features. The first method is referred to as the Mauch method, since it has been used in past studies and was developed by Mauch (9, 10, 12, 20, 21). The second method described is the cross-correlation method and the final method is the autocorrelation method.

Mauch Method

The Mauch method has been used in past research and is based on the following equation:

$$D(t) = S(t) - \frac{S(t - \tau) + S(t + \tau)}{2} = S(t) - \overline{S}_\tau(t) \tag{1}$$

where $S(t)$ is the cumulated velocity at time t , calculated as $S(t) = \int_{t_0}^t v(t') dt'$, $v(t)$ is the measured traffic velocity at

time t , t_0 is the time at the beginning of the observation period, τ is an arbitrary time constant with $\tau = 7$ min and $D(t)$ is the deviation detected by the Mauch method (further explanations are given below). Note that in (9, 10, 12, 20, 21) the analysis is based on flow rather than velocity.

It can be seen from equation 1 that $D(t)$ can be interpreted as the difference between the cumulated velocities, where $S(t)$ is the cumulated velocity, and the remainder of the right hand side is the cumulated velocity if the speed is assumed to be constant for the interval $(t - \tau; t + \tau)$. Transformation of Equation 1 also yields:

$$D(t) \sim \int_{t-\tau}^t v(t') dt' - \int_t^{t+\tau} v(t') dt' \tag{2}$$

Equation 2 shows that the deviation $D(t)$ can be calculated as the difference between the areas marked by the solid and the dashed lines in Figure 2.

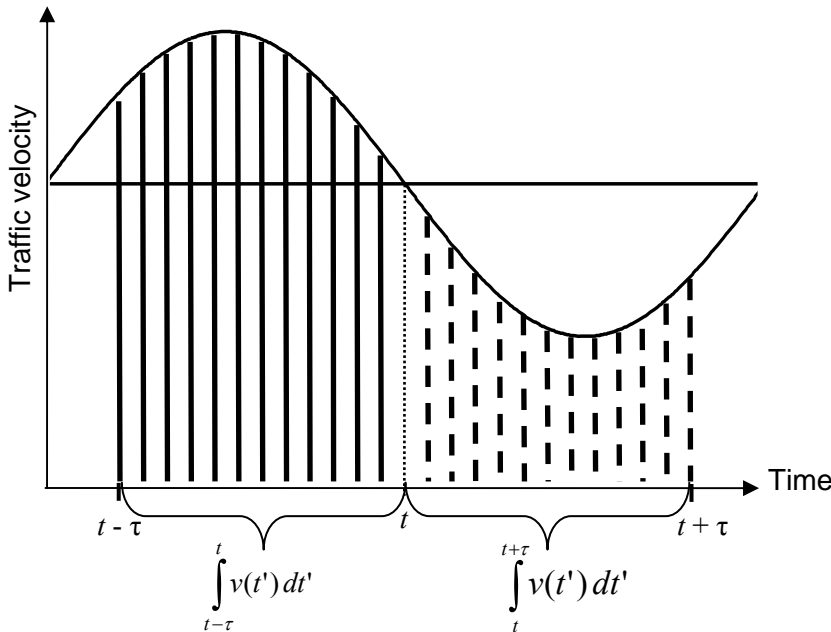


FIGURE 2 Illustration of Mauch method.

Equation 2 and Figure 2 suggest that the deviation $D(t)$ has a maximum peak if a transition from high to low traffic velocity takes place. Similarly $D(t)$ has a minimum if there is an increase from low to high speed. Therefore this methodology can be used in a heuristic way in order to detect the presence of traffic oscillations. In addition the time of the oscillation’s passage at a particular point (detector) can be recorded within the limits of the data aggregation.

Once the passage of an oscillation is measured at two or more locations whose spacing is known, the oscillation propagation speed can be calculated within the limits of the data aggregation. In (9, 10, 12, 20, 21) 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 3. About 20 minutes of data from detectors 6 and 7 on the M4, on November 2, 1998 were used to create the plot. The propagation of the oscillations is illustrated by the solid straight lines. Their slope is the propagation speed of the oscillations. The dashed lines show other possible interpretations of their propagation. Thus the velocities

obtained by this method are based on subjective interpretation.

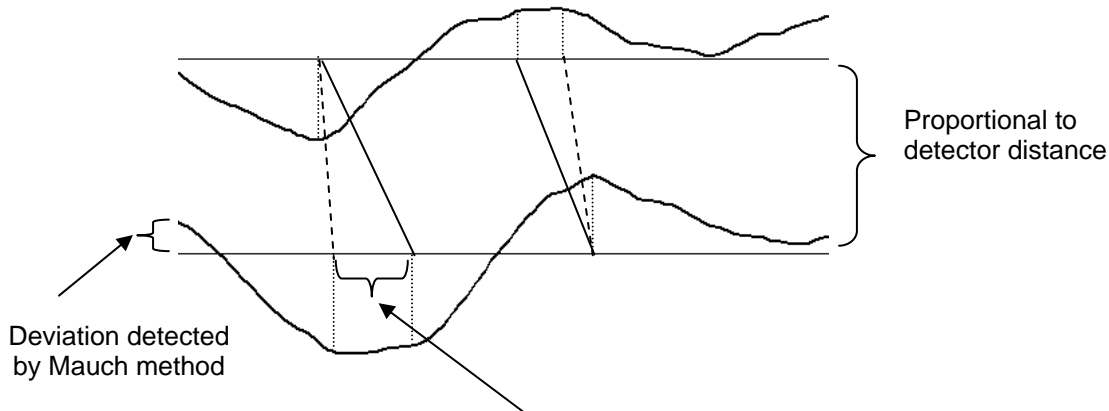


FIGURE 3 Uncertainty of Mauch method for identification of propagation velocity.

Cross-correlation Method

In the previous section a method was described to illustrate how traffic oscillations can be detected. It was also 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 now introduced as a refinement of the Mauch method. It will be referred to as the cross-correlation method and was used similarly in (14, 15).

Since oscillations propagate through the freeway network, 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. 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.

In practice, due to influence factors such as noise or data aggregation 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 between them can be calculated. The time shift referring to the highest correlation is interpreted as the travel time of the oscillations (more precisely, of the waves).

The previous explanations were based on one hypothetical traffic oscillation. If real data is used, several additional issues must be considered. First, 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, these differences are expected to be low. The result obtained is assumed to be an average travel time. Second, 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 is discrete. This aspect is also true for the Mauch method and for the autocorrelation method (explained below). It can be shown however, that the magnitudes of the relative error are notably lower for these two methods than it is for the cross-correlation method.

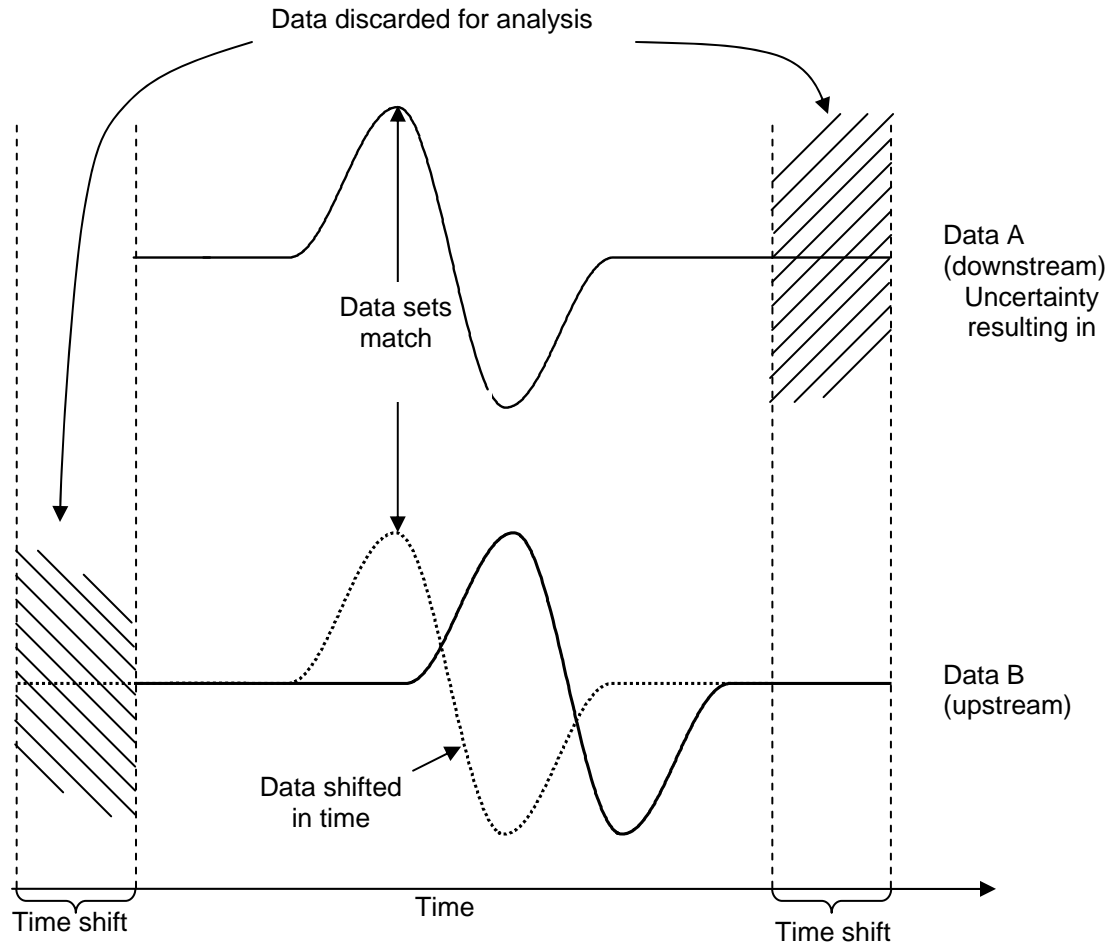


FIGURE 4 Illustration of hypothetical oscillation.

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. Periodic components of a signal can be identified by autocorrelation. This is demonstrated in Figure 5 in which a hypothetical periodic signal is illustrated. As shown, it matches with itself if it is shifted in time by a multiple of the oscillation period. Therefore a peak in the autocorrelation of the data indicates that it repeats itself to certain extent after the respective time shift.

Hence, periodicity of the autocorrelation allows one to determine the periodicity of the original data. Thus the period can be identified by the time shift corresponding to a peak. A similar approach was used in (15). In that work, the power density spectrum (i.e. the Fourier transformation of the autocorrelation) was used rather than the autocorrelation.

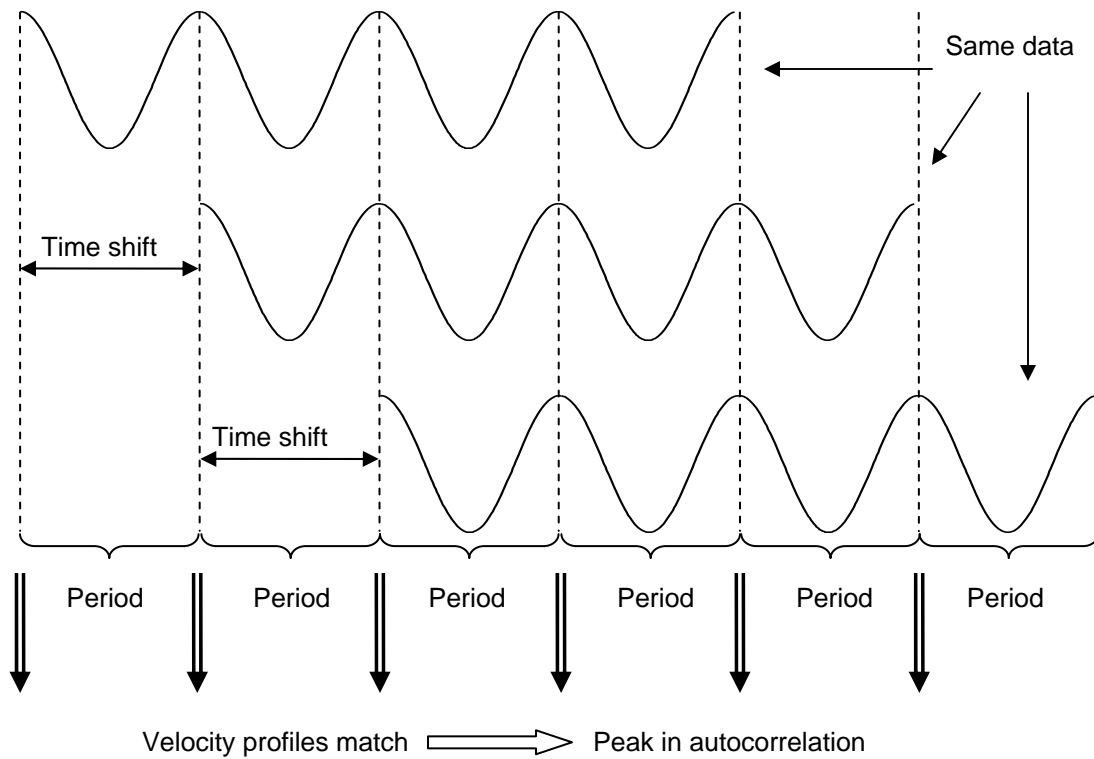


FIGURE 5 Illustration of autocorrelation applied to a periodic signal.

ANALYSIS

Based on the literature review and above discussion, the analysis for this paper consisted of four basic steps. First for each site, data from a suitable number of days was extracted and analyzed such that congested conditions could be identified. Once congested conditions were identified, oscillations were visually identified using the Mauch method, which revealed propagation velocities. Oscillation velocities were also measured using the cross-correlation method, and finally, oscillation cycle time periods were measured using the autocorrelation method.

Detection of Congested Traffic Conditions

Previous research has identified definitive ways of detecting transitions from freely-flowing to congested conditions (23, 24, 25, 26, 27). Therefore, the first step in this research was to identify congested regimes within the time-space plane. Figure 6 shows an example speed plot from the M4 on November 2, 1998. First, low speed regimes were identified using a time-space diagram of the measured traffic speed. Second, the low speeds were verified by plotting them over time for each detector. As described in (23), oblique plots were used to verify the time at which the transitions to and from congested conditions occurred. All further analysis has been performed with data identified as congested by this method.

Visual Detection of Oscillations

In order to visualize oscillations, the Mauch method has been applied to the data from the three sites. Figure 7 shows sample results from the M4, November 2, 1998. By analyzing a total of 18 days across the three sites, several main observations were made. First, oscillations occur regularly and propagate upstream against the direction of travel. This is illustrated by the lines in Figure 7 which represent waves. The slope of these lines represents the propagation velocity of these waves. Second, the propagation speed of the waves (indicated by the slope of the lines in Figure 7) is between 11.1 and 15.7 km/h. The arithmetic mean speed is 14.2 km/h and the median is 14.4 km/h. Third, Figure

7 indicates that oscillations appear about every 10 to 13 minutes for the analyzed day. Such oscillations were found for all sites by this method and hence can exist in all three countries.

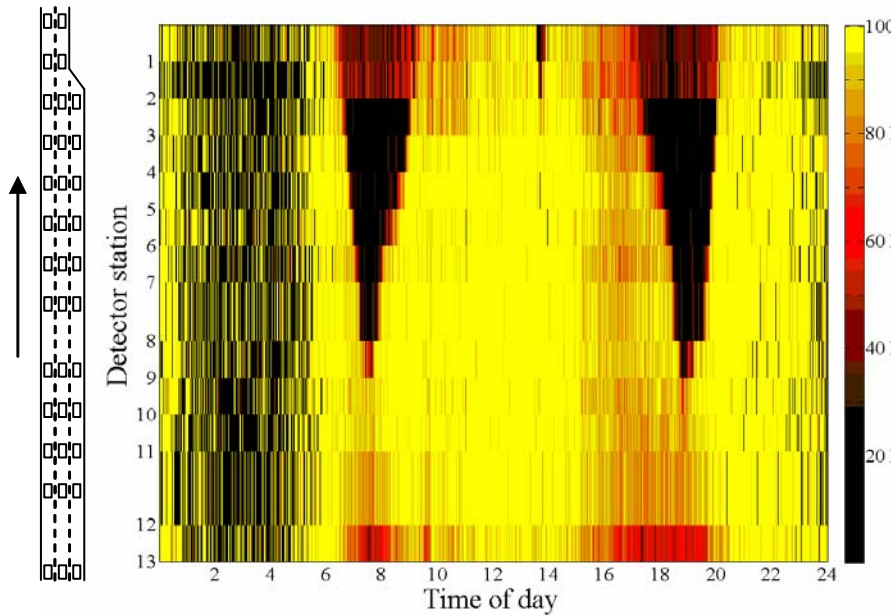


FIGURE 6 Detecting congested traffic features for M4 November 2, 1998.

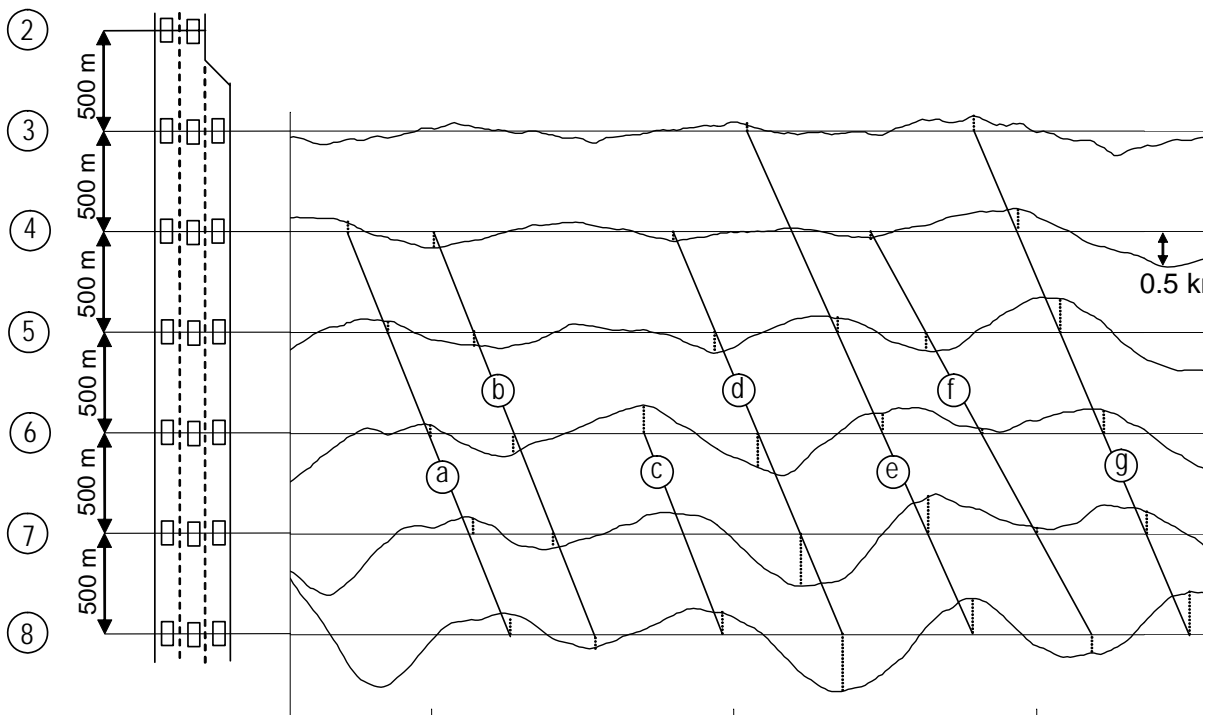


FIGURE 7 Velocity by cross-correlation.

As further verification of the propagation velocity, the cross-correlation method was applied to the data described above. Figure 8 shows a sample of the cross-correlation plots for the M4 on November 2, 1998. The cross-

correlation method was applied to data from the M4 for the seven days analyzed. Table 2 summarizes the results. As shown, the average speeds range between 12.4 and 16.0 km/h with an arithmetic mean of 13.8 km/h and a median of 13.4 km/h, similar to the propagation velocity detected by the Mauch method (14.2 vs. 14.4 km/h).

The cross-correlation method was also applied to the data from OR 217. Data was applied from detectors that are close enough together that the results of the cross-correlation method are clear and as far apart as possible. The results are also given in Table 2. The average propagation velocity shown in the last row is calculated by:

$$\bar{u} = \frac{\sum_i t_i}{\sum_i s_i} \quad (3)$$

where \bar{u} is the propagation velocity of the oscillation, t_i is the travel time of the oscillations for segment i and s_i is the length of segment i . As shown in the table, the average oscillation 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.

Finally, Table 2 shows the results of the cross-correlation method when applied to data from the A9. The average propagation speeds of the oscillations range between 10 and 17.9 km/h. The arithmetic mean is 15.6 km/h, and the median is 16.8 km/h.

TABLE 2 Propagation Speed (km/h) of Oscillations Identified by Cross-Correlation Method

M4 Detectors	11/2/98	11/3/98	11/4/98	11/5/98	11/9/98	11/10/98	11/11/98
	18:31–19:31	7:11–7:58	7:14–8:20	8:51–9:59	7:16–8:04	7:03–8:15	7:11–8:11
3–8	12.9	13.4					
3–7			14.7	16.0	12.9	12.4	14.1
OR 217 Detectors	3/8/05	4/18/05	9/1/05	9/16/05	9/16/05	9/22/05	9/26/05
	7:43–8:33	7:30–8:31	15:07–17:44	7:42–8:53	14:49–18:26	7:28–8:51	7:35–9:04
7–8		18.0	--	21.1	--		
6–7	19.5					19.5	20.6
5–6		18.0		20.0	15.0		
4–5			19.6		19.6		
Average	19.5	18.0	19.6	20.6	17.2	19.5	20.6
A9 Detectors	6/27/02	6/28/02	7/3/02	7/4/02	7/5/02		
	16:00–19:01	12:48–18:10	16:40–18:30	16:25–18:30	12:37–13:59		
16–17				--			
15–16			--		--		
14–15	17.9	--					
13–14				17.0			
12–13			10.0		16.5		
11–12	--	16.8	--				

Oscillation Period by Autocorrelation

The final component of this study was to determine the oscillation period using the autocorrelation method described above. The results of the autocorrelation method applied to data from the M4 can be found in Table 3. It can be seen that the results found with the Mauch method coincide with the results of the autocorrelation method (for the day presented: 11.7 to 12.2 min by the autocorrelation method; 10–13 min by the Mauch method). For all jams, the measured periods range between 2.0/8.0 min and 12.2 min (i.e. 120 s/480 s and 730 s). The arithmetic mean is 9.0 min (540 s) and the median is 8.5 min (510 s).

The autocorrelation method was also applied to data from OR 217. The results are also summarized in Table 3. The periods range between 3.0 min (180 s) and 5.7 min (340 s). The arithmetic mean is 4.0 min (242 s) and the median is 3.7 min (220 s).

Finally, the results of the autocorrelation method applied to data from the A9 are shown in Table 3 as well. For the A9, the periods were much longer, and ranged between 10 min and 31 min. The arithmetic mean is 21.8 min

and the median is 20/21 min. It should be noted that since the oscillation period is site-specific, no definitive country-specific differences can be identified based only on Table 3.

TABLE 3 Period Results from Autocorrelation Method

M4 Detector	11/2/98 18:31–19:31	11/3/98 7:11–7:58	11/9/98 7:16–8:04	11/11/98 7:11–8:11
3	120 s	--	530 s	--
4	--	--	520 s	--
5	730 s	--	510 s	--
6	720 s	500 s	460 s	590 s
7	710 s	500 s	480 s	--
8	700 s	510 s		
OR 217 Detector	3/8/05 7:43–8:33	4/18/05 7:30–8:31	9/22/05 7:28–8:51	9/26/05 7:35–9:04
8	--	--	280 s	--
7	180 s	260 s	300 s	--
6	--	--	--	180 s
5	220 s	--	--	220 s
4	--	--	340 s	--
A9 Detector	6/28/02 12:48–18:10	7/3/02 16:40–18:30	7/4/02 16:25–18:30	7/5/02 12:37–13:59
11	20 min		30 min	20 min
12	19 min	--	--	--
13	--	21 min	31 min	--
14			--	10 min

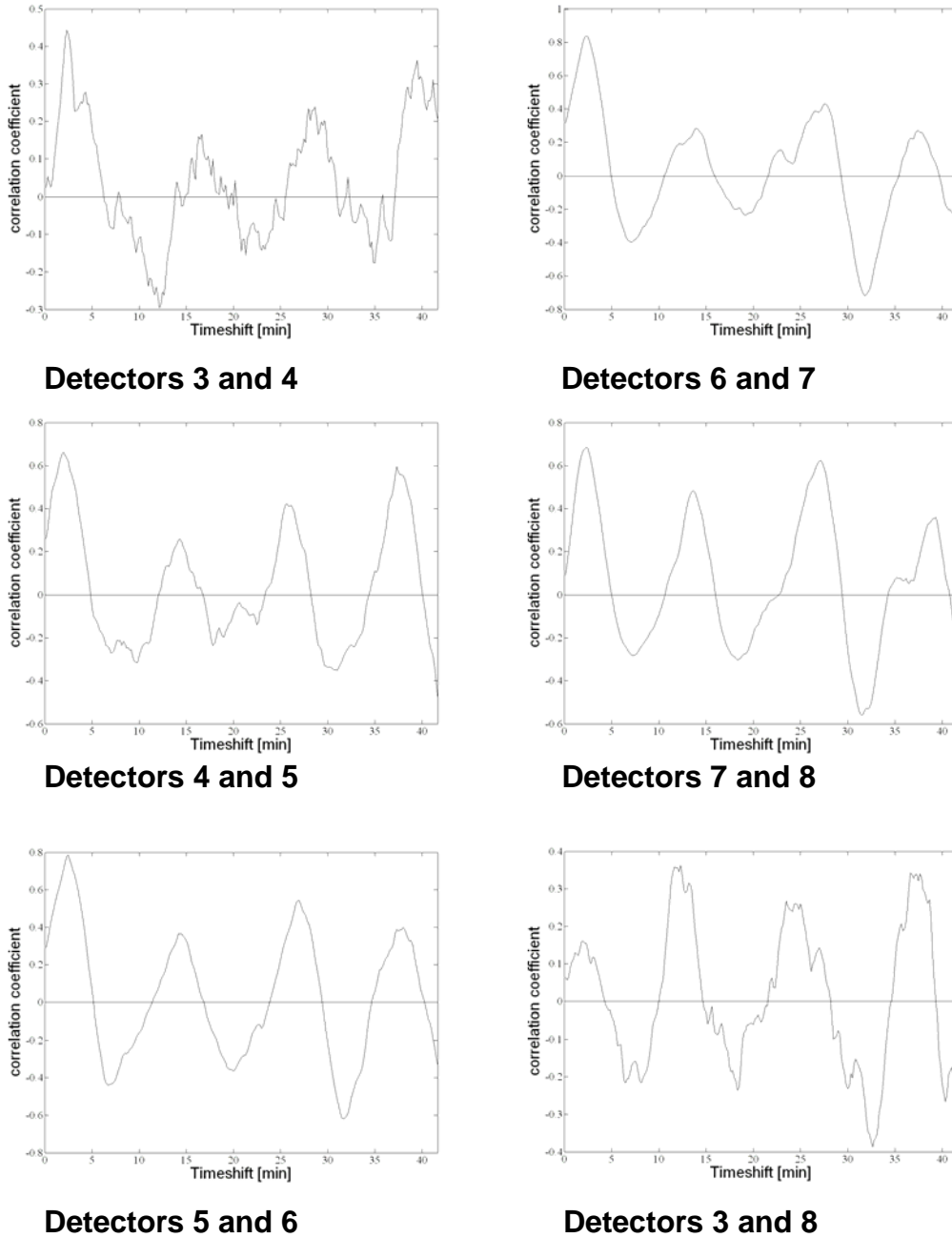


FIGURE 8 Cross-correlation analysis for November 2, 1998, 18:31–19:31.

CONCLUSIONS

The objective of this paper was to empirically measure features of freeway traffic oscillations in three different countries in order to reveal possible differences (or similarities) of note. Oscillation propagation velocities were measured over a total of 18 days at three sites. From this analysis, traffic oscillations were found to propagate at speeds of about 19–20 km/h on OR 217, 16 km/h on the A9, and 14 km/h on the M4. In addition to the heuristic method used in past research, this paper was able to confirm the oscillation propagation velocities definitively using cross-correlation.

These results are of the same magnitude as those found in the literature. If these results can be generalized for given countries (i.e. they are not site specific) this means that oscillations propagate upstream with a higher velocity in the US than they do in Germany. Furthermore, the analysis also showed that traffic oscillations propagated slower on the M4 than on the other sites. However, without further research on different sites, a general statement on the propagation velocity in the UK is not yet possible. Further empirical research is needed for a comparison of the propagation velocity in the UK with other countries.

Further consideration has been given to possible reasons that higher oscillation propagation velocities were found at the US site. As shown in Figure 9, the propagation velocity of traffic oscillations can be illustrated using the fundamental diagram, it is given by the slope of the congested regime (right hand side). Since the propagation velocity differs between two countries, this means that the respective fundamental diagrams do not necessarily coincide. However, without further analysis, no definitive statement can yet be made regarding how the diagrams differ. The following idea might give one explanation, but it still needs to be verified or rejected by further research.

For explanation purpose a triangular shaped diagram is assumed. As can be seen in Figure 9, a higher maximum flow (i.e. capacity) yields to a higher propagation velocity. Similarly a different maximum density k_{\max} also affects the propagation velocity. Therefore, this suggests that the capacity of a freeway segment can be associated with higher oscillation propagation speeds. In addition, a higher jam density (possibly due to shorter vehicle lengths) can be associated with lower oscillation propagation speeds. As explained earlier, the HCM (17) and the HBS (18) suggest a higher per lane capacity for US freeways than for German highways which is consistent with the higher oscillation speed found in the US than in Germany. Since the idea mentioned is not yet verified with data, further country specific analysis on the freeway capacity in Germany and the US should be performed for verification or rejection.

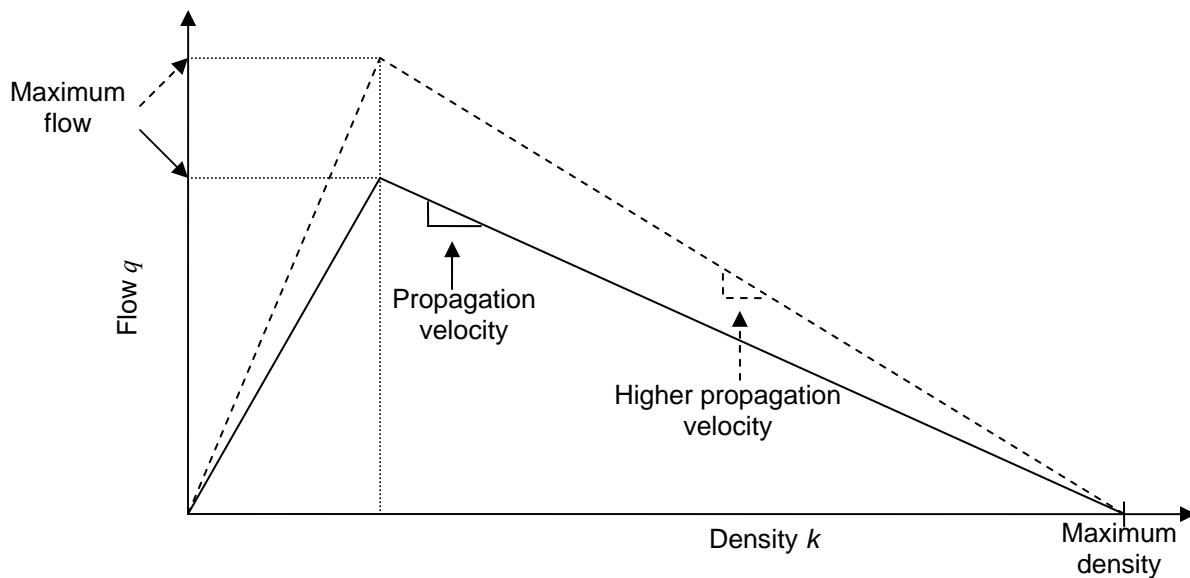


FIGURE 9 Fundamental diagram.

The methods used in this paper facilitated the computation of oscillation frequency in a definitive way. From the analysis of 18 days' data at three sites, the periods obtained by the autocorrelation method were in the following ranges: for the M4 the oscillation period was between 8–12 min. For the OR 217 site, the period ranged between 3–6 min. Finally, for the A9 autobahn in Germany the oscillation frequency range was notably longer, between 10–30 min. These results indicate that traffic oscillations appear with a frequency on the M4 and OR 217 which is considerably higher than on the A9.

The magnitudes of the periods identified in this analysis are supported by the literature. However, since it is very likely that traffic oscillation frequency is site-specific final conclusions cannot yet be made whether the oscillation period is generally lower in the US than in the UK and in Germany. Further research on different sites should be conducted to examine this possibility.

Even though this paper analyzes several aspects on traffic oscillations, their mechanisms are still not fully discovered. Since they seem to be key elements for understanding many aspects of traffic flow theory, the authors highly encourage further research in this field.

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