Empirical Measurement of Freeway Oscillation Characteristics

An International Comparison

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A country-specific analysis of freeway traffic oscillations was conducted. Loop detector data from sites in the United States, Germany, and the United Kingdom were analyzed. With the use of a method applied in previous work, traffic oscillations were identified in all three countries. Calculation of the cross-correlation coefficient revealed that they traveled upstream at speeds of about 19 to 20 km/h at the U.S. site, 16 km/h at the German site, and 14 km/h on the U.K. freeway. Similar magnitudes were found in the literature verifying the hypothesis that they propagated faster in the United States than in Germany. Furthermore, an oscillation frequency was identified by calculation of the data's autocorrelation. However, since the oscillation frequency was 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 appeared every 8 to 12 min on the M4 (U.K. site), every 10 to 30 min on the A9 (German site), and every 3 to 6 min on OR-217 (U.S. site). Although the magnitudes of the latter two countries were supported by the literature, further empirical research on several different sites should be pursued to draw final conclusions.

To maintain and increase the safety, predictability, and efficiency of the transportation system, major investments have been made in the construction of additional road infrastructure. Current economics and politics 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 development and deployment of these require a thorough understanding of traffic-flow phenomena, research has been performed resulting in various traffic models. One of these 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 could help resolve some of the remaining questions.

Different countries have different standards for infrastructure, vehicle mix, and driving rules; driver behavior may also vary. Thus, traffic flow might exhibit different characteristics. Since traffic models are intended to describe 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).

BACKGROUND

A traffic oscillation usually is defined as stop-and-go or slow-and-go conditions. In this paper, a pattern in traffic flow is 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 elsewhere (1, 4), including a definition of space–mean speed, also referred to as traffic speed in this paper.
- The traffic is congested. Information about defining congestion, also referred to as jammed or queued traffic in this paper, is given by Daganzo (5).
- The observed pattern propagates upstream against the direction of travel.

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

Causes of Oscillations

Previous research investigated possible reasons for traffic oscillations. Two related explanations in the available literature describe the possible origin of traffic oscillations. Some researchers have explained traffic oscillations through car-following behavior. Microscopic car-following models are often used to explain traffic oscillations

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(*4, 6–8*). In those models, oscillations form just upstream of a bottleneck and increase in amplitude because of large reaction times of drivers and overreactions by drivers propagating against the direction of travel. Other related research shows that traffic oscillations are caused by lane changing. Ahn identifies lane changing as the primary factor for traffic oscillations (*9*). 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 consider three main characteristics of traffic oscillations that are relevant for empirical measurements and for modeling purposes: amplitude, propagation velocity, and frequency.

The first feature to be considered is the amplitude of oscillations in freeway traffic. Previous research attempted to determine conclusively whether oscillations grow or shrink in amplitude as they travel through the traffic stream. Car-following models (*4, 6–8*) and some empirical observations (*9*) have shown that oscillations do increase in amplitude while propagating upstream. [Ahn used a measure other than amplitude (*9*). However, a relation between this measure and amplitude appears 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 ramps and off ramps on the amplitude of oscillations. Ahn found that on ramps do have an effect on the amplitude of traffic oscillation through a pumping effect (*9*). 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 was performed for the latter case by Ahn (*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 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

(*2, 5, 9–15*). 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 is referred to as period. Table 1 shows the results of a literature review on the oscillation period.

In work by Ahn (*9*), Lindgren (*10*), and Mauch (*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 Schönhof and Helbing (*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 by Kim and Zhang (*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.

A final issue relating two oscillation features has been addressed in previous research. A relation between amplitude and frequency is described by Gartner et al., who state that long periods are accompanied by large oscillation amplitudes and high frequencies result in low amplitudes (*7*).

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 context of freeway capacity, The *Highway Capacity Manual* (HCM) serves as a guide for the design and operation of transportation facilities and infrastructure in the United States and other countries (*17*). The *Handbuch für die Bemessung von Straßenverkehrsanlagen* (HBS) is the German equivalent of the HCM (*18*). Both manuals use level of service (LOS) to quantify how well a facility is operating. A comparison for freeway traffic with a truck percentage of 10% found that the thresholds for the same LOS are associated with higher per-lane flows in the HCM than in the HBS (*19*). In addition, the maximum per-lane flow (threshold

TABLE 1 Literature Review: Period of Traffic Oscillations

Study	Period (min)	Study Site	Data Year	Comment
(*13*)	3	U.S. (Holland Tunnel)	NA	Frequency directly upstream of the bottleneck (high frequencies might fade out upstream as explained in the text).
(*9*)	4–8	U.S. (I-80)	2003	Frequency analysis was not object of analysis. Results were obtained by looking at the plots.
(*15*)	4	U.S. (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.

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 U.S. 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 refer to the same quality standard. Therefore, further site-specific research is needed to verify whether a difference in capacity exists.

DESCRIPTION OF DATA

To draw comparisons between reproducible characteristics of traffic oscillations, freeway loop detector data from three sites were analyzed for this study. Data were available from sites in the United States, Germany, and the United Kingdom. Site maps are presented in Figure 1.

The U.S. site is located on OR-217, a freeway southwest of Portland, Oregon. Data (velocity, count, and occupancy) were available for the whole section (11.2 km) in 20-s aggregates. The data include all freeway lanes and on ramps. Sensors on off ramps were not installed. The data were available for download from PORTAL (*20*), an online data archive for the Portland metropolitan area. (Data in PORTAL are provided by the Oregon Department of Transporta-

tion.) Analysis was done for the southbound direction for 6 days in March, April, and September 2005.

The PORTAL data were provided by double loop detectors. However, it is uncertain 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, and it ran 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 were available from double loop detectors between Kilometer 528.2 and Kilometer 513.3 in 1-min aggregates and were 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 for most on ramps 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 U.K. site is eastbound motorway M4 near London. Data from double loop detectors were available for the section between Kilometer 23.2 and Kilometer 16.2 for 7 days in November 1998 and were provided by the U.K. 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
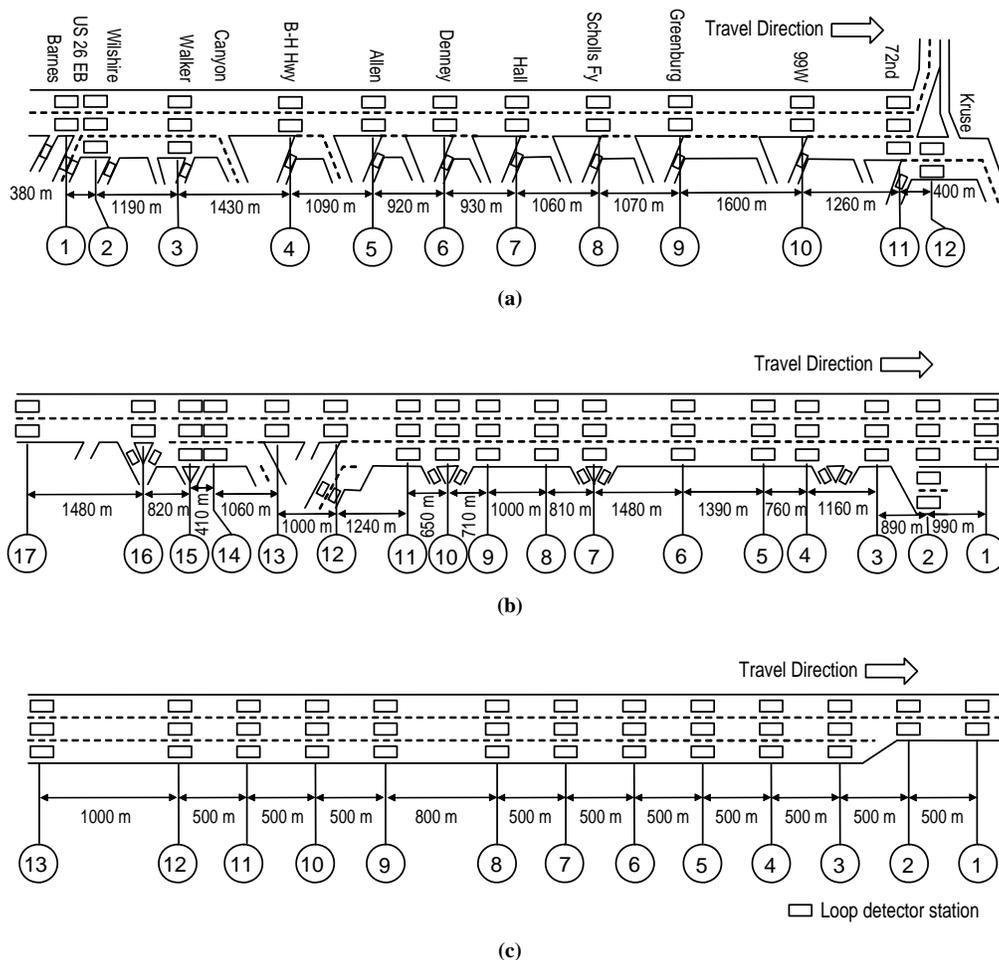

FIGURE 1 Site maps: (*a*) OR-217, (*b*) A9, and (*c*) M4.

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.

METHODOLOGY

Since traffic data generally are 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 is referred to as the Mauch method, since it has been used in past studies and was developed by Mauch (*9, 10, 12, 21, 22*). The second method is cross-correlation, and the final method is autocorrelation.

Mauch Method

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

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

where

$S(t)$ = cumulated velocity at time t, calculated as

$$S(t) = \int_{t_0}^{t} v(t')dt'$$

$v(t)$ = measured traffic velocity at time t;
t_0 = time at the beginning of the observation period;
τ = arbitrary time constant with $\tau = 7$ min; and
$D(t)$ = deviation detected by the Mauch method.

In previous work (*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

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

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.

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 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 previous work (*9, 10, 12, 21, 22*), the Mauch method was applied to identify the propagation speed of oscillations. Therefore, the deviation $D(t)$
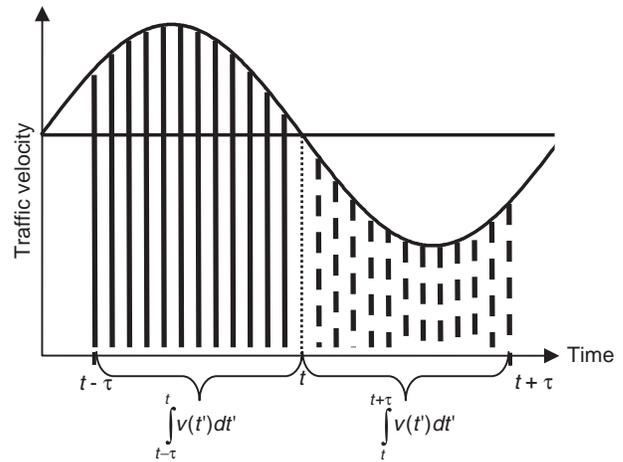

FIGURE 2   Illustration of Mauch method.

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 min of data from Detectors 6 and 7 on the M4 from 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.

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. This is the cross-correlation method, which was used similarly by Coifman and Wang (*14*) and Mika et al. (*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 are 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, because of influence factors such as noise and data aggregation, the velocity profile at the two detector stations will not perfectly match. 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 are 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
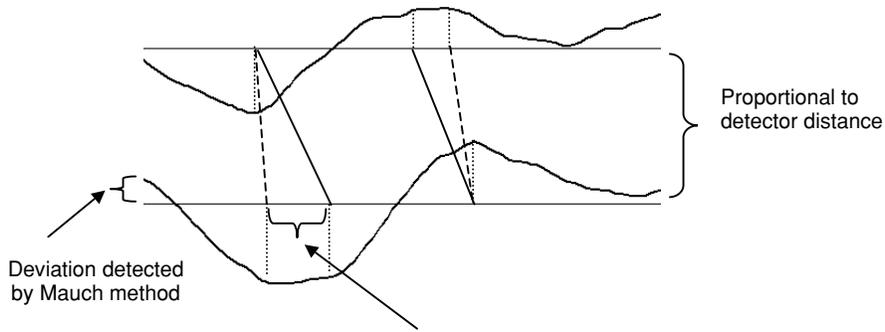
FIGURE 3 Uncertainty of Mauch method for identification of propagation velocity.

is assumed to be an average travel time. Second, data sets can be compared only for a time shift that is a multiple of the aggregation time. Hence, the travel time and therefore the propagation velocity obtained by this method are discrete. This aspect is also true for the Mauch method and for the autocorrelation method. 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.

Autocorrelation Method

For the cross-correlation method, two different data sets (i.e., data from two locations) are compared. If one data set is compared with itself, shifted in time, this is 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 a 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 by Mika et al. (*15*). In that work, the power density spectrum (i.e., the Fourier transformation of the autocorrelation) was used rather than the autocorrelation.
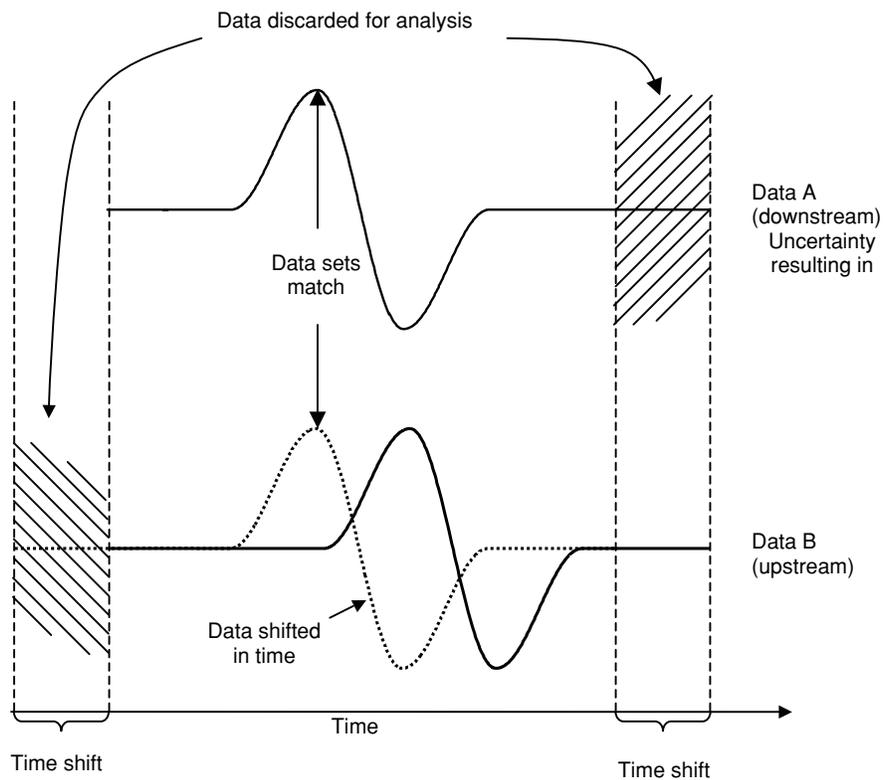

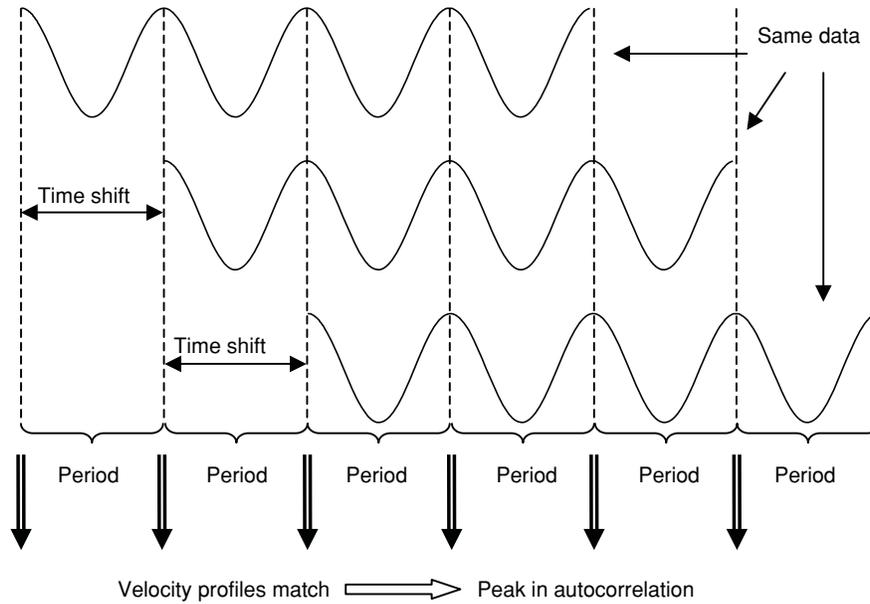FIGURE 4 Illustration of hypothetical oscillation.

FIGURE 5   Illustration of autocorrelation applied to periodic signal.

ANALYSIS

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

Detection of Congested Traffic Conditions

Previous research identified definitive ways of detecting transitions from freely flowing to congested conditions (*23–27*). 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 by 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 by Cassidy and Windover (*23*), oblique plots were used to verify the time at which
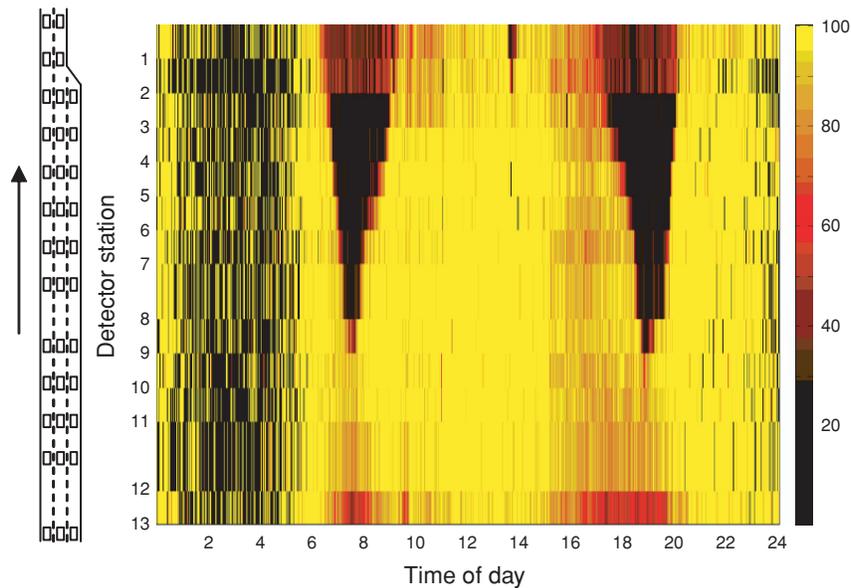

FIGURE 6   Detecting congested traffic features for M4, November 2, 1998.

the transitions to and from congested conditions occurred. All further analysis has been performed with data identified as congested by this method.

$$\bar{u} = \frac{\sum_i \text{tt}_i}{\sum_i s_i} \tag{3}$$

where

$\bar{u}$ = propagation velocity of the oscillation,
tt_i = travel time of the oscillations for segment i, and
s_i = 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.

Visual Detection of Oscillations

To visualize oscillations, the Mauch method was applied to the data from the three sites. Figure 7 shows sample results from the M4 for 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 min for the analyzed day. Such oscillations were found for all sites by this method and hence can exist in all three countries.

As further verification of the propagation velocity, the cross-correlation method was applied to the described data. Figure 8 is 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 7 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 versus 14.4 km/h).

The cross-correlation method was also applied to the data from OR-217. Data were 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

Oscillation Period by Autocorrelation

The final component of this study was to determine the oscillation period by using the autocorrelation method. The results of the autocorrelation method applied to data from the M4 are shown in Table 3. 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 to 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).
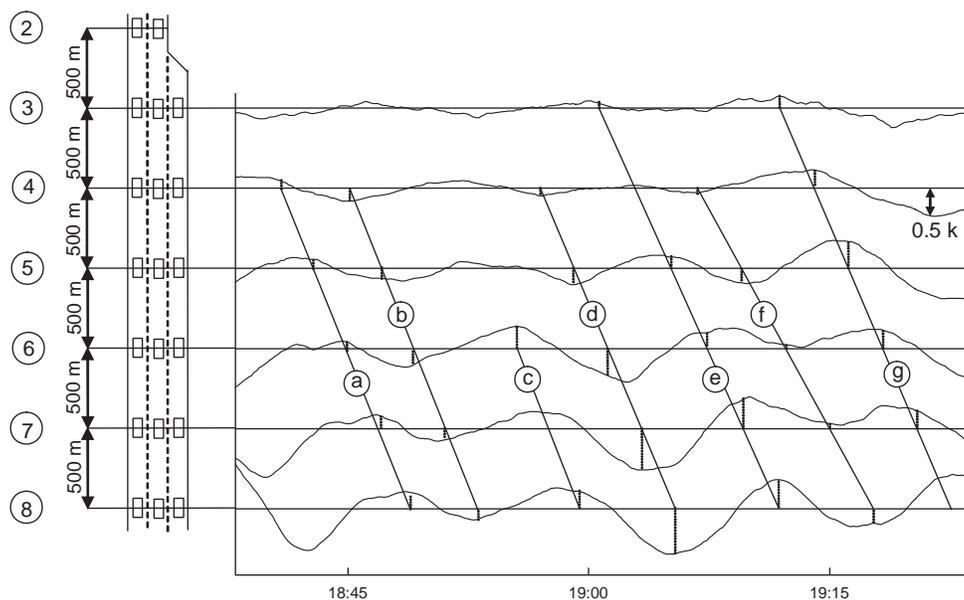

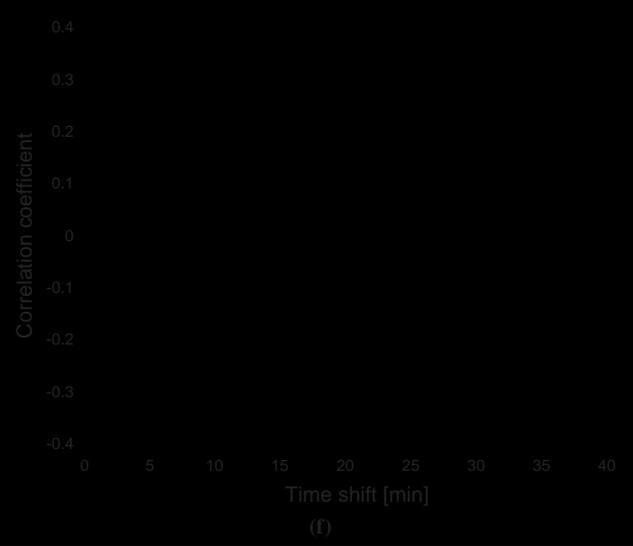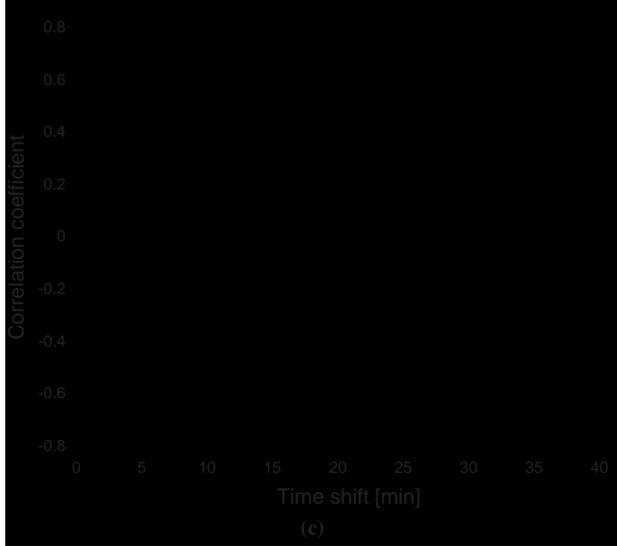FIGURE 7   Velocity by cross correlation.

(a)

Correlation coefficient

Time shift [min]

0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3

0　5　10　15　20　25　30　35　40

(d)

Correlation coefficient

Time shift [min]

1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

0　5　10　15　20　25　30　35　40

(b)

Correlation coefficient

Time shift [min]

0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6

0　5　10　15　20　25　30　35　40

(e)

Correlation coefficient

Time shift [min]

0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6

0　5　10　15　20　25　30　35　40

(c)

Correlation coefficient

Time shift [min]

0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8

0　5　10　15　20　25　30　35　40

(f)

Correlation coefficient

Time shift [min]

0.4
0.3
0.2
0.1
0
-0.1
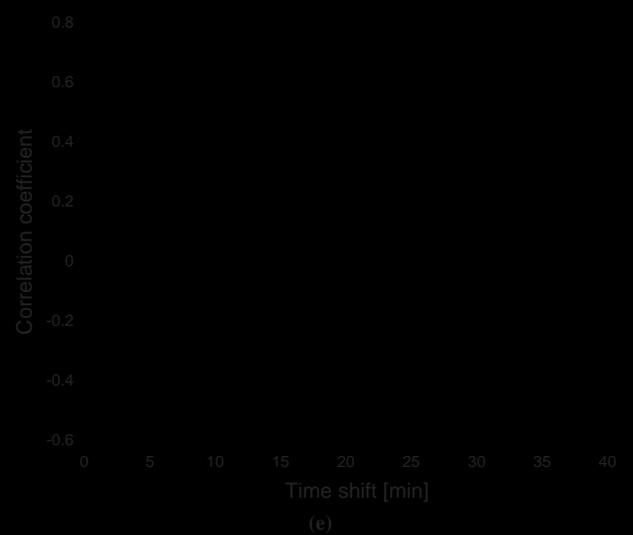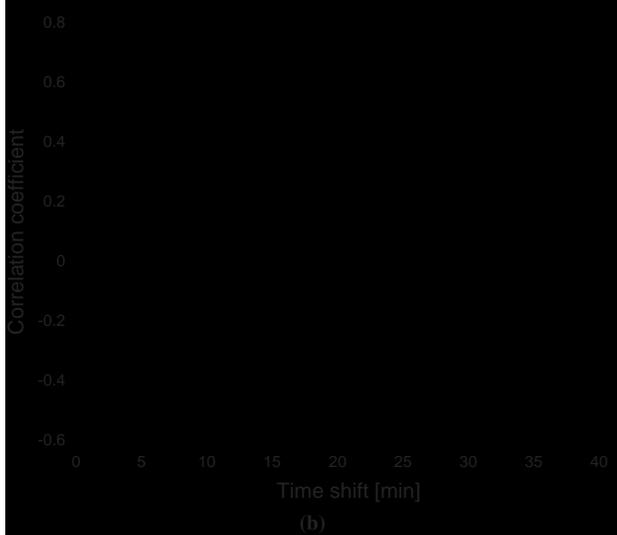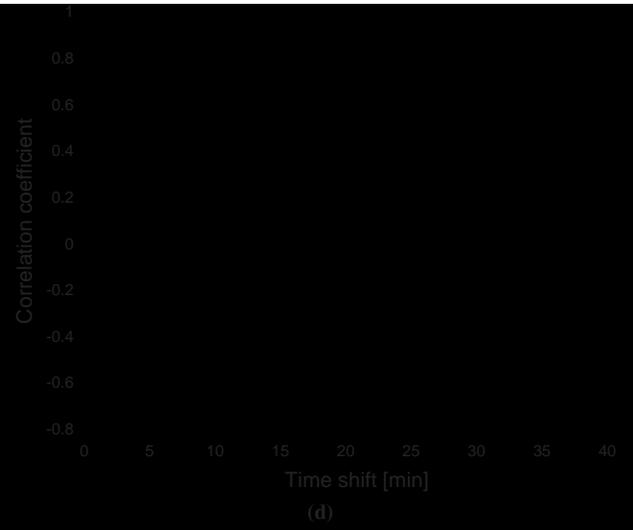-0.2
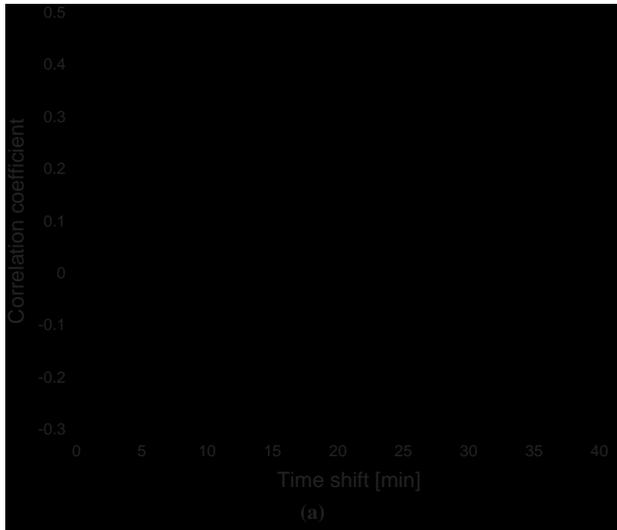-0.3
-0.4

0　5　10　15　20　25　30　35　40

TABLE 2 Propagation Speed of Oscillations Identified by Cross-Correlation Method

M4 Detectors	11/2/98 18:31–19:31	11/3/98 7:11–7:58	11/4/98 7:14–8:20	11/5/98 8:51–9:59	11/9/98 7:16–8:04	11/10/98 7:03–8:15	11/11/98 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 7:43–8:33	4/18/05 7:30–8:31	9/1/05 15:07–17:44	9/16/05 7:42–8:53	9/16/05 14:49–18:26	9/22/05 7:28–8:51	9/26/05 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 16:00–19:01	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
16–17				—	
15–16			—		—
14–15	17.9	—			
13–14				17.0	
12–13			10.0		16.5
11–12	—	16.8	—		

Finally, the results of the autocorrelation method applied to data from the A9 are shown in Table 3. For the A9, the periods were much longer and ranged between 10 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 only on the basis of Table 3.

TABLE 3 Period Results of 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

CONCLUSIONS

The objective for this study was to empirically measure features of freeway traffic oscillations in three countries and to reveal possible differences (or similarities). Oscillation propagation velocities were measured for a total of 18 days at three sites. From this analysis, traffic oscillations were found to propagate at speeds of about 19 to 20 km/h on OR-217 in the United States, 16 km/h on the A9 in Germany, and 14 km/h on the M4 in the United Kingdom. In addition to the heuristic method used in previous research, this study confirmed the oscillation propagation velocities definitively by 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), then oscillations propagate upstream with a higher velocity in the United States than they do in Germany. Furthermore, the analysis also showed that traffic oscillations propagated more slowly on the M4 than on the other sites. However, without further research on different sites, a general statement on the propagation velocity in the United Kingdom is not yet possible. Further empirical research is needed for a comparison of the propagation velocity in the United Kingdom with other countries.

Further consideration has been given to possible reasons that higher oscillation propagation velocities were found at the U.S. site. As shown in Figure 9, the propagation velocity of traffic oscillations can be illustrated by 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, 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 may give one explanation, but it needs to be verified or rejected by further research.

For explanation purposes, a triangular diagram is assumed. As shown in Figure 9, a higher maximum flow (i.e., capacity) yields to a higher propagation velocity. Similarly, a different maximum density
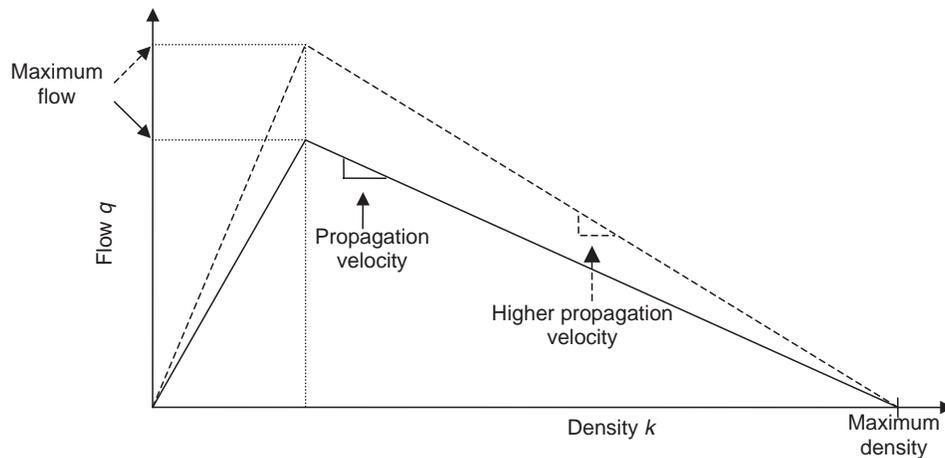
FIGURE 9   Fundamental diagram.

k_{max} 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 U.S. freeways than for German highways, which is consistent with the higher oscillation speed found in the U.S. 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 United States should be performed for verification or rejection.

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 and 12 min. For the OR-217 site, the period ranged between 3 and 6 min. For the A9 Autobahn in Germany, the oscillation frequency range was notably longer, between 10 and 30 min. These results indicate that traffic oscillations appear with a frequency on the M4 and OR-217 that 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 likely that traffic oscillation frequency is site specific, final conclusions cannot yet be made whether the oscillation period is generally lower in the United States than in the United Kingdom and in Germany. Further research on different sites should be conducted to examine this possibility.

Although 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 encourage further research in this field.

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