Empirical analysis of the causes of stop-and-go waves at sags

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Abstract

Stop-and-go waves are spatially-confined regions of low traffic speed that propagate upstream at a constant velocity. The occurrence of stop-and-go waves on freeways has negative impacts on both travel time and traffic safety. Sags are freeway sections along which gradient changes significantly from downwards to upwards. Stop-and-go waves often emerge on the uphill section of sags, both in uncongested and congested traffic conditions. According to previous studies, the formation of stop-and-go waves at sags can be caused by local changes in car-following behaviour as well as disruptive lane changes. However, it is not clear which of those two causes is more frequent. The aim of this paper is to identify the primary factor triggering stop-and-go waves at sags. To this end, we analyse vehicle trajectories collected by means of video cameras on a three-lane sag of the Tomei Expressway (Japan), identifying the causes of formation and growth of stop-and-go waves on the study site. The results show that the primary factor triggering stop-and-go waves is related to car-following behaviour. This finding shows the relevance of developing systems to assist drivers in performing the acceleration task at sags.

1 Introduction

Stop-and-go waves are spatially-confined regions of low traffic speed that propagate upstream at a constant velocity of 15-25 km/h [1, 2]. The occurrence of stop-and-go waves on freeways has negative impacts on travel time and traffic safety [3]. *Sags* are freeway sections along which gradient changes significantly from downwards to upwards in the direction of traffic [4]. Traffic flow capacity is significantly lower at sags than at flat sections [5, 6]. Because of that, sags become bottlenecks in freeway networks, causing the formation of congestion in conditions of high traffic demand. The mechanism of formation of congestion at sags has two phases [5, 7, 8]. In the first phase, congestion forms on the fast lane(s) of the uphill section in the form of stop-and-go waves. In the second phase, congestion spreads from the fast lane(s) to the slow lane(s). Stop-and-go waves also emerge within congested traffic [9].

The primary factor triggering the formation of stop-and-go waves at sags has not been clearly identified yet. Several studies show that drivers unintentionally change their car-following behaviour on the uphill section of sags. More specifically, drivers tend to reduce speed [4, 5] and keep longer distances to the leading vehicle than expected [10, 11]. Some authors suggest that those local changes in car-following behaviour are the dominant factor triggering stop-and-go waves on the uphill section of sags [5, 10]. In contrast, other authors suggest that disruptive lane changes may be the primary triggering factor [12].

The objective of this paper is to determine whether the primary factor triggering stop-and-go waves at sags is related to car-following behaviour or to lane changes, both in congested and uncongested traffic conditions. This is important to understand the mechanism of stop-and-go wave formation at sags, and to develop effective measures to improve traffic flow efficiency and traffic safety at that type of bottlenecks.

To that end, we analyse a set of vehicle trajectories collected by means of video cameras on a three-lane sag of the Tomei Expressway (Japan) during the start of the morning rush hour, before and after the formation of persistent congestion. We analyse the evolution of speed over time on each lane at several locations as well as individual vehicle trajectories, identifying and classifying the causes of stop-and-go wave formation and growth.

The paper will show that the primary factor triggering stop-and-go waves at sags is related to car-following behaviour; lane changes seem to be a less significant triggering factor. This finding shows the relevance of developing systems to assist drivers in performing the acceleration task at sags [13].

The rest of this paper is structured as follows. Section 2 describes the main causes of stop-and-go waves at sags according to the scientific literature. Section 3 presents the characteristics of the study site and the trajectory data. Section 4 describes the data analysis method used to identify the main factor triggering stop-and-go waves at the study site. Section 5 reports the results of the analysis. Section 6 discusses the implications of the results, taking into account the limitations of the data. Section 7 presents the conclusions of this study.

2 Background

In general, the occurrence of traffic congestion on freeways is caused by a combination of three elements [14]: a) high traffic volume; b) a spatial inhomogeneity on the freeway that generates a capacity bottleneck; and/or c) a temporary disturbance of the traffic flow. Several empirical studies show that traffic flow capacity can be significantly lower at sags than at flat sections having the same number of lanes (up to 30% lower) [1, 5, 6]. Because of their lower capacity, sags become bottlenecks in freeway networks, causing the formation of congestion in conditions of high traffic demand. Generally, in freeways with keep-left or keep-right rules, the mechanism of congestion formation at sags consists of two phases: i) formation of congestion on the inner (fast) lane(s) of the uphill section; and ii) spreading of congestion to the outer (slow) lane(s) [5, 7, 8].

In the first phase, congestion forms on the fast lane(s) of the uphill section. The main reason why congestion emerges first on the fast lane(s) instead of the slow lane(s) is related to the characteristics of lane flow distribution. In freeways with keep-left or keep-right rules, with high demand and uncongested traffic, flows tend to be much higher on the fast lane(s) than on the slow lane(s), hence flows are closer to capacity on the fast lane(s) [5, 15, 16]. In those conditions, small perturbations can destabilise traffic flow and trigger the formation of congestion in the form of stop-and-go waves [5, 8].

In the second phase, congestion spreads from the fast lane(s) to the slow lane(s). Some authors suggest that the spreading of congestion is caused by the fact that, when stop-and-go waves emerge on the fast lane(s), some drivers migrate to the less crowded slow lane(s) in order to avoid stopping [5, 7, 8]. The spreading of congestion to all lanes causes a significant decrease in total outflow rates (due to the capacity drop phenomenon [17]) and the formation of a queue upstream of the bottleneck [5, 8]. The head of the queue stays on the first 500-1000 m downstream of the bottom of the sag [5, 12]. Within the queue, small

traffic flow disturbances can trigger the formation of stop-and-go waves [9].

The primary factor triggering stop-and-go waves at sags (both in uncongested and congested traffic conditions) has not been clearly identified yet (see Figure 1). Several studies show that two significant changes in car-following behaviour occur when vehicles reach the uphill section. First, drivers tend to reduce speed [4, 5, 10, 12]. Second, some drivers keep longer headways than expected given their speed [10, 11]. These local changes in car-following behaviour seem to be unintentional [11]. They are caused by a combination of two factors: increase in the resistance force due to the increase in freeway slope, and insufficient acceleration operation by drivers [5, 11]. Some authors suggest that the above-mentioned changes in car-following behaviour can be the direct cause of the disturbances that trigger the formation of stop-and-go waves on the uphill section of sags [5, 10]. However, other authors suggest that at sags stop-and-go waves can also be triggered by disruptive lane changes [9, 12]. Some of those disruptive lane changes may indirectly be caused by the above-mentioned changes in car-following behaviour, since vehicle decelerations on the uphill section may locally modify the differences in traffic speed between lanes, incentivising lane changes [12]. However, no empirical evidence of a causal relationship between changes in car-following behaviour and lane changes at sags has been presented in the scientific literature.

To summarize, it is not clear whether the primary factor triggering stop-and-go waves at sags is related to car-following behaviour or to lane changes. Identifying the primary factor is important to understand the mechanism of stop-and-go wave formation at sags and to develop effective measures to improve traffic flow efficiency and traffic safety at that type of bottlenecks.

[Figure 1 about here.]

3 Data characteristics

This section describes the empirical data used to analyse the causes of stop-and-go waves at sags. The data consist of a set of vehicle trajectories on a freeway sag section in Japan during the morning peak hour. Section 3.1 describes the study site, and Section 3.2 describes the characteristics of the vehicle trajectories.

3.1 Study site

The study site is a westbound stretch of the Tomei Expressway (near Tokyo, Japan) located between kilo-posts (KP) 20.0 and 23.5 km. It contains a downhill section followed by an uphill section. Figure 2(a) shows the vertical alignment profile of the study site. The downhill approach is 1.8 km long, and it consists of a steeper section (-1.9% gradient) followed by a gentler section (-0.5% gradient). The bottom of the sag is located at KP 22.03 km. The uphill section is around 1.5 km long. Its gradient is +2.4% on the first 1000 m, but it decreases on the last 500 m. The study site has three lanes used by regular traffic (median, center and shoulder) plus an emergency lane (see Figure 2(b)). The median lane is the fastest and right-most lane (note that in Japan drivers have the obligation to drive on the left unless they are overtaking). There are no ramps nor lane drops in or near the site. The expressway curves gently to the right at the study site, which may restrict the line-of-sight for drivers, but only to a limited extent.

[Figure 2 about here.]

3.2 Vehicle trajectories

The study site is equipped with 10 video-cameras located in sequence between KP 21.67 and 22.75 km, capturing the last 360 m of the downhill approach, the bottom of the sag and the first 720 m of the uphill section (see Figure 2(a)). The distance between consecutive cameras is around 120 m and the exact locations are known. Using a software tool developed by Patire [18], individual vehicles were identified in the video recordings of each camera, obtaining one passing time and lane per vehicle per camera location. Vehicle trajectories were constructed by combining the passing time and lane of each vehicle (rear bumper) at each camera location. This was done for the period 6:40h-7:05h on Friday, December 23rd, 2005, resulting in 2284 vehicle trajectories during the start of the morning peak hour, before and after the formation of persistent congestion on the study site. Note that the space and time resolution of the trajectories are limited due to the characteristics of the data collection and processing methods. Cameras are located around 120 m apart, and the passing time and lane of each vehicle are recorded only once per camera location. Therefore, space resolution is 120 m and time resolution varies between 4 and 12 s depending on vehicle speed.

4 Data analysis methods

In order to determine whether the primary factor triggering stop-and-go waves at the study site is related to car-following behaviour or to lane changes, we first analysed the evolution of vehicle speed over time at all camera locations, identifying the locations where stop-and-go waves form or grow in amplitude. Next, we analysed individual vehicle trajectories in order to determine the reasons why the vehicles that cause the formation or growth of stop-and-go waves decelerate, disrupting traffic. Insight on the causes of stop-and-go wave growth may help us to understand the causes of stop-and-go wave formation.

4.1 Calculation of vehicle speeds

The *speed* of a given vehicle between two consecutive locations was calculated as the distance between those two locations divided by the time that the vehicle takes to travel between them. Therefore, the speed of vehicle n between the locations of cameras $i-1$ and i is:

$$v_{n,i} = \frac{x_i - x_{i-1}}{t_n(x_i) - t_n(x_{i-1})}, \tag{1}$$

where: x_{i-1} and x_i are the locations of cameras $i-1$ and i, respectively; $t_n(x_i)$ and $t_n(x_{i-1})$ are the passing times of the rear bumper of vehicle n at locations x_i and x_{i-1}, respectively.

4.2 Identification of the causes of formation and growth of stop-and-go waves

A *speed disturbance* is a temporary decrease in the speed of vehicles passing a particular location on a particular lane. In this study, we defined a speed disturbance as a decrease in speed of 7 km/h or more within a short period of time, in line with Ahn and Cassidy [19]. A threshold of 7 km/h guarantees that small variations in vehicle speed are filtered out, whereas significant traffic flow perturbations are taken into account. A sensitivity analysis of that threshold was beyond the scope of our study. The occurrence of a speed disturbance is generally a sign of the occurrence of a traffic flow perturbation. In uncongested traffic, if a disturbance does not destabilise traffic flow, it generally propagates downstream. If a disturbance destabilises traffic flow or traffic flow is already congested, the disturbance typically propagates upstream at a constant speed of 15-25 km/h, creating a stop-and-go wave [2]. Sometimes the amplitude of stop-and-go

waves increases or decreases as they propagate [19]. In order to determine the triggering factors for the formation and growth of stop-and-go waves on the study site, we followed a multi-step method based on Ahn and Cassidy [19] (see Figure 3).

[Figure 3 about here.]

4.2.1 Identification of stop-and-go waves

To identify the presence of stop-and-go waves, we compared the evolution of vehicle speeds over time in all pairs of consecutive camera locations. This analysis was done separately for each lane. The presence of a stop-and-go wave results in a temporary decrease in the speed of vehicles passing a particular camera location over time. At the study site, the distance between consecutive video cameras is around 120 m. Therefore, if a stop-and-go wave propagates upstream at a speed of 15-25 km/h, a similar vehicle speed pattern is observed on the same lane at the next camera location in the upstream direction after 15-30 seconds. Figure 4(a) shows an example of stop-and-go wave. At the location of Camera 4, vehicle speed decreases from 85 to 28 km/h between t=438s and t=481s. A similar speed pattern is observed at the location of Camera 3 (upstream) with a time lag of around 15 seconds.

[Figure 4 about here.]

4.2.2 Identification of the locations where stop-and-go waves form and grow in amplitude

Once the presence of a stop-and-go wave was identified, we determined the location where the wave originated (if that location is within the area under camera surveillance). At that location, vehicle speed decreases without the presence of a similar speed pattern 15-30 seconds earlier on the same lane at the previous downstream camera location. We defined that a stop-and-go wave forms at a particular location if the speed at that location reaches values more than 7 km/h lower than at the preceding downstream camera location during the previous 30 seconds [19]. Figure 4(b) shows an example of formation of a stop-and-go wave, which later will propagate upstream (the latter cannot be observed in the figure). Vehicle speed stays between 35 and 40 km/h at the locations of Camera 7 and Camera 8 between t=1110s and t=1140s. At t=1140s, speed starts to decrease at the location of Camera 7, reaching 28 km/h at t=1158s. However, speed does not decrease at the location of Camera 8 (downstream) during the previous 30 seconds; actually, first speed stays

constant and later it increases. Therefore, a stop-and-go wave is formed between the locations of Camera 7 and Camera 8 without the influence of any downstream trigger.

We also determined the locations within the camera surveillance area where stop-and-go waves grow in amplitude as they propagate upstream. The growth of a stop-and-go wave at a particular location results in a significantly greater decrease in speed than at the previous camera location. We defined that a stop-and-go wave grows at a particular location if it causes the speed at that location to decrease to values more than 7 km/h lower than on the same lane at the previous downstream camera location [19]. Figure 4(c) shows an example of stop-and-go wave growth. At the location of Camera 10, vehicle speed drops from 47 to 38 km/h between t=990s and t=998s. At the location of Camera 9 (upstream), speed follows a similar pattern with a time lag of around 30 seconds: speed drops from 49 to 39 km/h between t=1017s and t=1034s. However, after t=1034s, speed does not increase (as it does at the location of Camera 10 after t=998s), but it keeps decreasing, reaching 28 km/h at t=1065s. This indicates that the stop-and-go wave grows in amplitude between the locations of Camera 9 and Camera 10.

4.2.3 Determination of the causes of stop-and-go wave formation and growth

Once we identified the locations where stop-and-go waves form and grow, we determined the causes why they do so. To this end, we followed a two-step approach. First, we identified the vehicles that decelerate and cause the formation or growth of each stop-and-go wave. This was done by manually comparing the speeds of each individual vehicle in each pair of consecutive camera locations on the same lane (see Figure 5(a) and Figure 5(c)). Second, we determined the cause why those vehicles decelerate. This was done by manually analysing individual vehicle trajectories to check whether any vehicles move to the subject lane in front of the vehicles that decelerate and cause the formation or growth of each stop-and-go wave. If that is the case, we concluded that the cause is one or more lane-changing manoeuvres (see Figure 5(d)). If that is not the case, we concluded that the cause is related to car-following behaviour (see Figure 5(b)). Note that we assumed that both types of causes are mutually exclusive.

[Figure 5 about here.]

4.3 Test of statistical significance

The primary factor triggering stop-and-go waves at the study site was identified in two steps. First, we counted the number of instances in which the causes of stop-and-go wave formation or growth are related to: i) car-following behaviour; and ii) disruptive lane changes. Thus, we identified the most frequent cause. Second, we tested whether the frequency of stop-and-go waves caused by car-following behaviour phenomena was significantly different from the frequency of stop-and-go waves caused by lane changes. This is comparable to testing whether a coin is fair: from a series of outcomes, it is tested whether the relative frequency of one of the sides is so high that it can be considered unlikely. A two-tailed binomial test is suitable to do so. Based on a series of outcome observations, that type of test determines whether: a) two outcome categories are equally likely to occur (null hypothesis); or b) two outcome categories are not equally likely to occur (alternative hypothesis) [20]. Applied to our case, the test shows whether observed differences in frequency between the two causes of stop-and-go waves result purely from chance or from the fact that one cause is actually more frequent than the other. The p-value indicates how unlikely the outcome should be to reject the null hypothesis. If the p-value is higher than the significance level (for which we chose 5%), the null hypothesis cannot be rejected. Instead, if the p-value is lower than the significance level, the null hypothesis is rejected.

5 Results

In this section, we present the results of the analysis of the causes of stop-and-go wave formation and growth at the study site.

5.1 Identification of stop-and-go waves

In total, thirteen stop-and-go waves have been identified in the data, all of them on the center and median lanes. No stop-and-go wave has been identified on the shoulder lane. All the identified stop-and-go waves have their origin either on the uphill section or farther downstream (see Figure 6). Five stop-and-go waves have been identified on the center lane, of which four have their origin within the section under camera surveillance and the other one originates farther downstream (see Figure 6(a) and Table 1). Eight stop-and-

go waves have been identified on the median lane, of which five have their origin within the area under surveillance and the rest originate farther downstream (see Figure 6(b) and Table 1). Note that some of the stop-and-go waves seem to occur simultaneously on the center and median lanes (compare Figure 6(a) with Figure 6(b)).

[Table 1 about here.]

Seven of the thirteen stop-and-go waves that have been identified on the center and median lanes form in uncongested traffic (waves 1, 2, 6, 7, 8, 9 and 10 in Figure 6(a) and Figure 6(b)). The remaining six waves form in congested traffic (waves 3, 4, 5, 11, 12 and 13 in Figure 6(a) and Figure 6(b)). The traffic speed indicates whether traffic flow is congested or uncongested (see also [18]).

[Figure 6 about here.]

5.2 Causes of stop-and-go wave formation

The cause of formation of eight of the nine stop-and-go waves that have their origin within the section under camera surveillance (both in the center and median lanes) is related to car-following behaviour (see Figure 5(a), Figure 5(b), Figure 6(a), Figure 6(b) and Table 1). One stop-and-go wave on the center lane is triggered by lane-changing vehicles coming from the shoulder lane (see Figure 6(a) and Table 1). The two-tailed binomial test shows that the causes of stop-and-go wave formation are more frequently related to car-following behaviour than to lane changes at the 5% significance level (p-value $= 0.04 < 0.05$).

5.3 Causes of stop-and-go wave growth

The thirteen stop-and-go waves observed in the data set have been identified to grow in amplitude in nine cases. In eight of those nine cases, the cause of growth is related to car-following behaviour (see Figure 6(a), Figure 6(b) and Table 1). One stop-and-go wave grows on the median lane as a result of lane-changing maneuvers performed by vehicles coming from the center lane (see Figure 5(c), Figure 5(d), Figure 6(b) and Table 1). The two-tailed binomial test shows that the causes of stop-and-go wave growth are more frequently related to car-following behaviour than to lane changes at the 5% significance level (p-value $= 0.04 < 0.05$).

6 Discussion

The results presented in Section 5 must be interpreted with caution, due to the reduced sample size and the limited scope of the data. First, the sample size is small (only thirteen stop-and-go waves were identified in the data), which may reduce the significance of the results. The results would be more conclusive if additional trajectory data with more stop-and-go waves were available. Second, we analysed microscopic flow data of one particular sag. The causes of stop-and-go waves can be site-specific, therefore our findings can be generalized to other sags only to a certain extent. An analysis of data from additional sites is necessary to draw a final conclusion regarding the transferability of our findings to other sags. If possible, the additional sites should be from other countries and include sags with different vertical alignment profiles and different number of lanes than our study site.

In spite of those data limitations, the findings presented in this study are important to understand traffic flow dynamics at sags. Our results indicate that the primary factor triggering stop-and-go waves at sags is related to car-following behaviour, whereas lane changes are a less significant triggering factor. We found evidence that lane-changing vehicles can disrupt traffic and trigger stop-and-go waves at sags, as suggested by other authors [12]. However, at our study site, the formation and growth of stop-and-go waves seem to be caused by lane changes only in a few cases (11%). In most cases (89%), the causes of stop-and-go wave formation and growth are related to car-following behaviour. This difference in frequency is statistically significant. Our results seem to be in line with the findings of Zheng *et al.* [9], who found that in most cases (66%) the cause of stop-and-go waves forming on the uphill section of a US freeway was related to car-following behaviour. The remaining waves (33%) were triggered by lane changes. That site also contains a merge and a diverge, which may explain why the percentage of stop-and-go waves triggered by lane changes is higher than in our study site.

Some studies found evidence that car-following behaviour changes significantly on the lower part of the uphill section at sags. Drivers tend to decelerate and keep longer headways than expected given their speed [4, 5, 10, 11]. Goñi Ros *et al.* [21] found evidence of those changes in car-following behaviour in the same trajectory data set used in this paper. Some authors suggest that those local changes in car-following behaviour are the primary triggering factor of stop-and-go waves at sags [5, 10]. It is important to note that due to the characteristics of our data and methodology, we could only determine whether the causes

of stop-and-go wave formation and growth are related to lane changes or to car-following behaviour. The hypothesis that the primary factor triggering stop-and-go waves at sags are the changes in car-following behaviour caused by the change in freeway gradient seems plausible. However, further research is necessary to identify the characteristics of the car-following behaviour phenomena that trigger stop-and-go waves at sags. For instance, some of the stop-and-go waves identified in this paper seem to occur simultaneously on the center and median lanes; the cause for that may be that drivers adapt their car-following behaviour to the traffic conditions on the adjacent lanes, triggering stop-and-go waves on their lane.

Alternatively, the cause for the simultaneous occurrence of stop-and-go waves on different lanes may be related to lateral driving behaviour. As explained in Section 2, when a stop-and-go wave emerges on a given lane, some drivers move to the other lanes in order to avoid stopping. Those lane changes may spread congestion to the target lanes [5, 7, 8]. Even if those lane changes do not directly disrupt traffic on the target lanes, they do cause an increase in flow. With higher flow, perturbations related to car-following behaviour are more likely to destabilise traffic flow and trigger stop-and-go waves.

7 Conclusions

Stop-and-go waves frequently emerge on the uphill section of sags, both in uncongested and congested traffic conditions. Previous studies suggest that the causes of stop-and-go waves at sags are related to: a) car-following behaviour; and/or b) disruptive lane changes. However, it is not clear which of those two triggering factors is dominant. We analysed vehicle trajectories collected by means of video cameras on a three-lane sag of the Tomei Expressway (Japan), identifying the causes of stop-and-go wave formation and growth on the study site. The results show that in most cases the factor triggering stop-and-go waves is related to car-following behaviour; disruptive lane changes are a less significant triggering factor. The car-following behaviour phenomena that trigger stop-and-go waves at sags may be related to the changes in car-following behaviour caused by the change in freeway slope, as suggested in the scientific literature. However, further research is necessary to validate that hypothesis. Our findings have important implications for the development of measures aimed at mitigating oscillatory traffic. Particularly, our findings show the relevance of developing systems to assist drivers in performing the acceleration task at sags [13].

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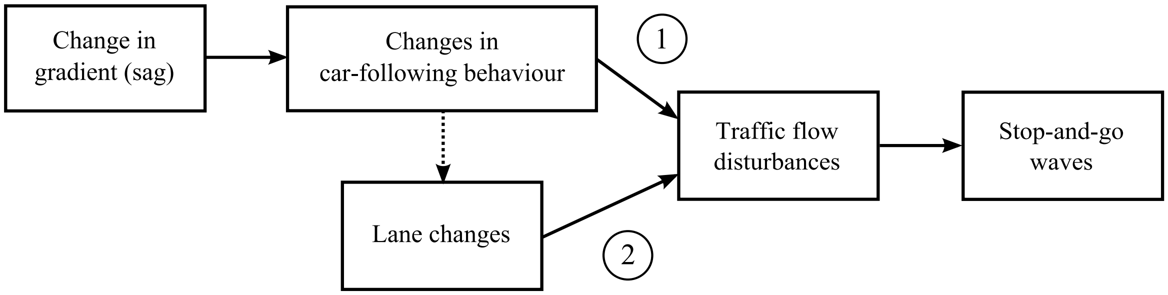
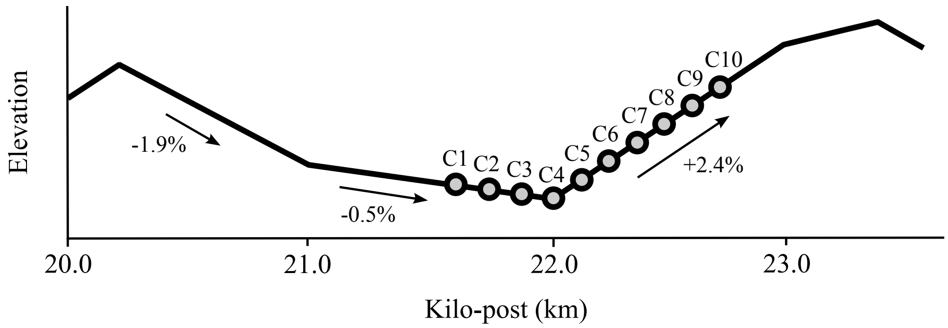
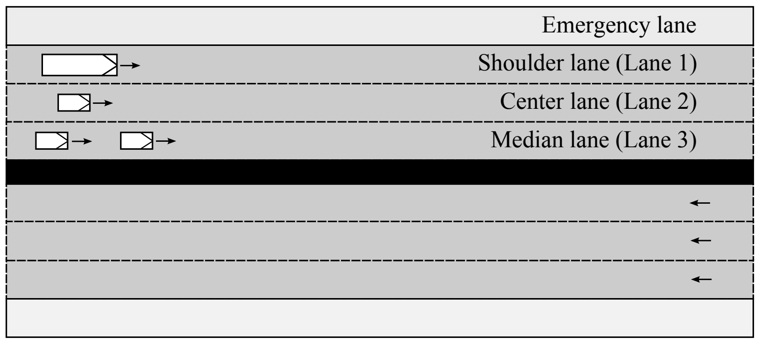


Figure 1: Factors triggering the formation of stop-and-go waves on the uphill section of sags (according to the scientific literature): 1) changes in car-following behaviour; and 2) disruptive lane changes.



(a) Vertical alignment profile and camera locations.



(b) Lane layout.

Figure 2: Layout of the study site.

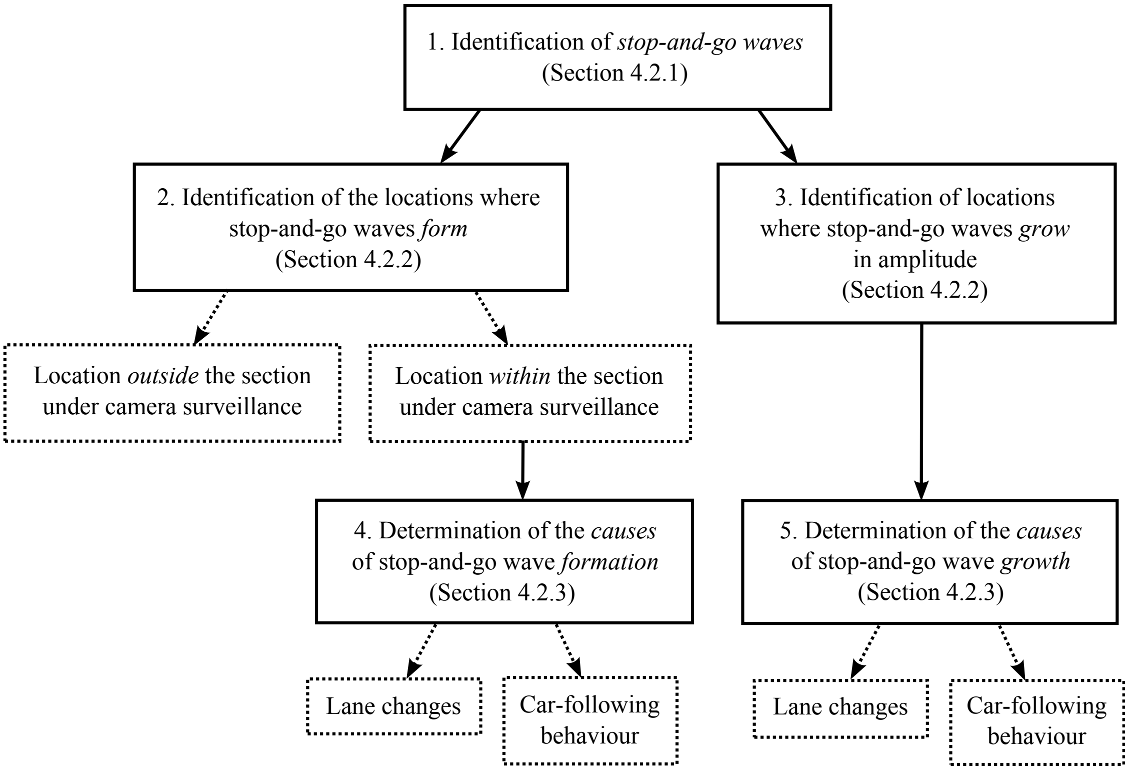
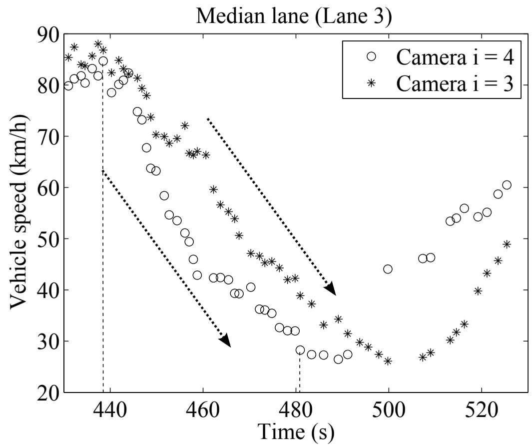
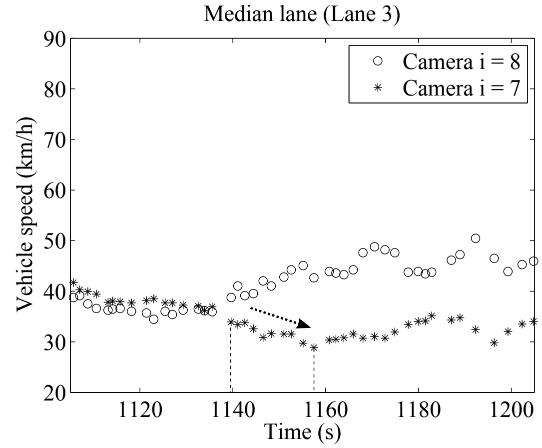


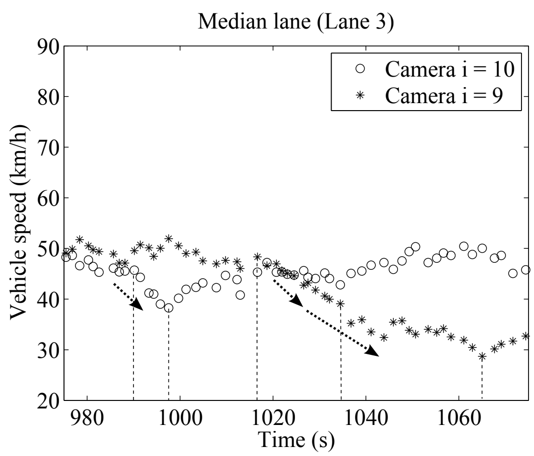
Figure 3: Steps to identify the causes of formation and growth of stop-and-go waves.



(a) Stop-and-go wave propagating upstream. Camera 3 is located upstream of Camera 4.

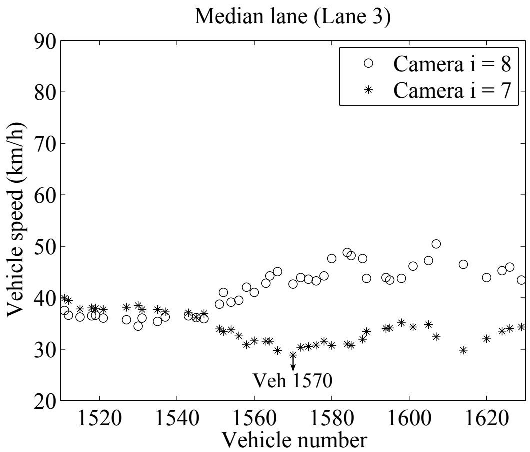


(b) Formation of a stop-and-go wave. Camera 7 is located upstream of Camera 8.

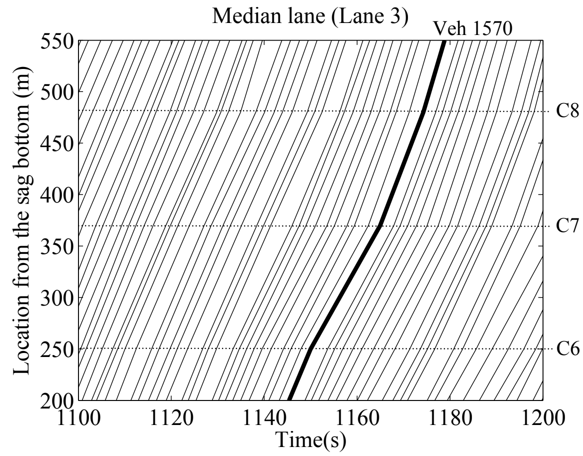


(c) Stop-and-go wave propagating upstream and growing in amplitude as it propagates. Camera 9 is located upstream of Camera 10.

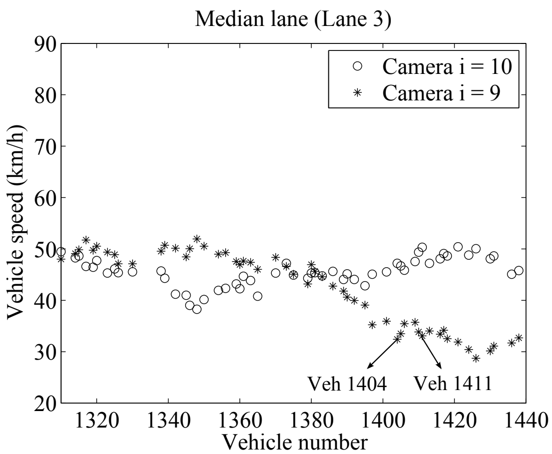
Figure 4: Examples of stop-and-go wave propagation (a), formation (b) and growth (c).



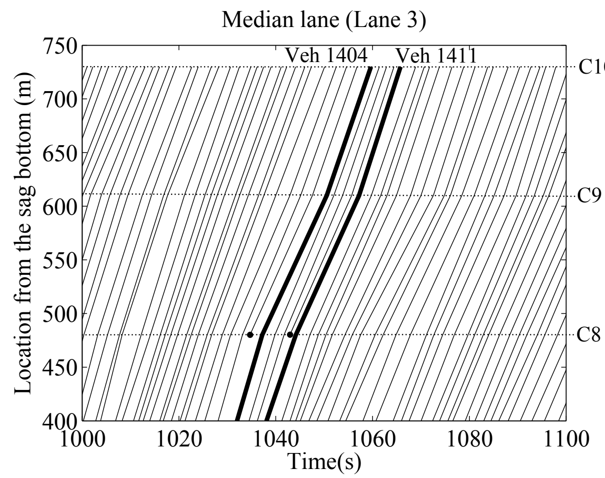
(a) Example of formation of a stop-and-go wave. Speed per vehicle number at the locations of cameras 7 and 8 on the median lane. Camera 7 is located upstream of Camera 8.



(b) Example of formation of a stop-and-go wave. Vehicle trajectories between the locations of cameras 6, 7 and 8 on the median lane.

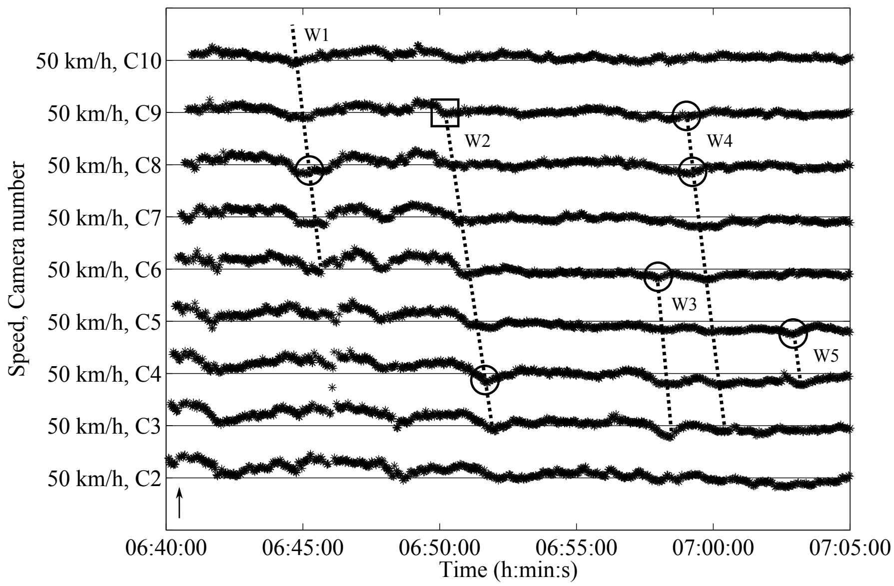


(c) Example of stop-and-go wave growth. Speed per vehicle number at the locations of cameras 9 and 10 on the median lane. Camera 9 is located upstream of Camera 10.

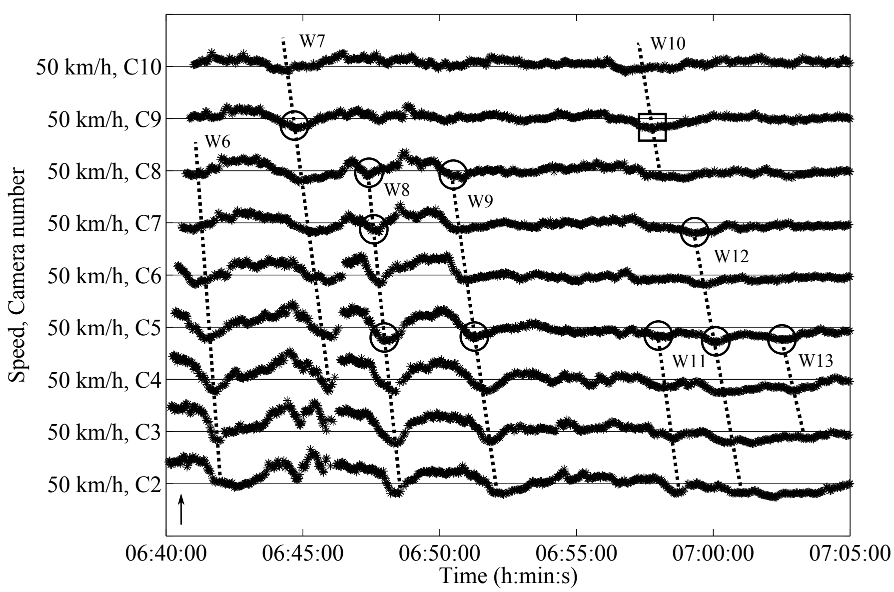


(d) Example of stop-and-go wave growth. Vehicle trajectories between the locations of cameras 8, 9 and 10 on the median lane. Small circles represent lane changes performed before a particular camera location.

Figure 5: Identification of the causes of stop-and-go wave formation and growth.



(a) Center lane.



(b) Median lane.

Figure 6: Speed deviation (from 50 km/h) of vehicles passing each camera location on the center and median lanes. Dashed lines indicate stop-and-go waves, which are numbered (W1, W2, etc.). Circles and squares indicate locations where stop-and-go waves form or grow in amplitude. Circles indicate that the cause for stop-and-go wave formation/growth is related to car-following behaviour. Squares indicate that the cause for stop-and-go wave formation/growth is related to disruptive lane changes. Camera 4 is located at the bottom of the sag.

	Center lane			Median lane		
	Origin identified	Origin not identified	Total	Origin identified	Origin not identified	Total
Stop-and-go waves	4	1	5	5	3	8
Cause of formation (CF/LC)	3/1			5/0		
Stop-and-go wave amplifications			3			6
Cause of amplification (CF/LC)			3/0			5/1

Table 1: Causes of stop-and-go wave formation and growth (CF stands for car-following behaviour; LC stands for lane changes).