Car-following Behavior at Sags and its Impacts on Traffic Flow

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ABSTRACT

Sags are freeway sections along which gradient changes significantly from downwards to upwards. Sags often become bottlenecks in freeways. With high traffic demand, congestion generally forms on the fast lane(s) of the uphill section and then it spreads to the slow lane(s). Previous studies suggest that the capacity of the fast lane(s) decreases on the uphill section due to changes in car-following behavior and an increase in the frequency of lane changes. However, it is not clear which of those two factors is dominant. The aim of this paper is to identify the primary factor triggering the formation of congestion at sags. To this end, we analyze vehicle trajectories collected by means of video cameras on a sag in Japan. First, we analyze the relation between average time headway and speed on the fast lanes at different locations. The results indicate that, at similar speeds, drivers tend to keep longer headways on the uphill section than on the downhill section. Therefore, lane capacity decreases on the uphill section. Second, we identify the causes of formation and growth of traffic flow disturbances on the fast lanes. The results show that in almost all cases the formation and growth of disturbances is triggered by car-following instabilities; disruptive lane changes are a less frequent triggering factor. We conclude that the capacity of the fast lanes decreases at sags primarily as a result of the changes in car-following behavior that occur on the uphill section.

1 INTRODUCTION

Traffic congestion has important negative effects on society, such as delays, accidents, air pollution and stress. During the last decades, many studies have been carried out in order to determine the causes of traffic jams and design effective strategies to mitigate congestion.

Sags are freeway sections along which gradient changes significantly from downwards to upwards in the direction of traffic *(1)*. In mountainous regions, congestion frequently forms at sags. The main reason is that the traffic flow capacity of sags is generally lower than that of flat sections *(2, 3)*. The lower part of the uphill section seems to be the main bottleneck *(4)*. At sags, congestion generally forms first on the fast (inner) lane(s) and then it spreads to the slow (outer) lane(s) *(2, 5, 6)*.

The factors that cause the formation of congestion on the fast lane(s) have not been clearly identified yet. Several studies show that drivers change their car-following behavior on the uphill section of sags. First, they tend to reduce speed *(1, 2)*. Second, they tend to keep longer distance headways than on the downhill section at similar speeds *(7, 8)*. As a result of these behavioral changes, lane capacity decreases on the uphill section *(2)*. In addition, some authors suggest that the above-mentioned changes in car-following behavior modify the differences in traffic speed between lanes, which may induce drivers to perform a higher number of lane changes, reducing lane capacity further *(2, 4)*. However, it is not clear whether changes in car-following behavior or lane changes are the dominant factor reducing the capacity of the fast lane(s) at sags.

The aim of this paper is to identify the primary factor triggering the formation of congestion at sags. To this end, we analyze a set of vehicle trajectories collected by means of video cameras on a three-lane sag of the Tomei Expressway in Japan during the morning rush hour. The center and median lanes are both considered to be fast lanes. Two types of analyses of microscopic flow characteristics are performed. First, we analyze the relation between average time headway and speed on the center and median lanes at different locations along the sag section. Second, we analyze the evolution of speed over time on the center and median lanes at several locations and individual vehicle trajectories, identifying the causes of formation and growth of traffic flow disturbances.

In the remainder of the paper, we will show that average car-following behavior changes considerably at the sag of the study site. On average, drivers tend to keep longer time headways on the uphill section than on the downhill section at similar speeds. As a result of these behavioral changes, the capacity of the center and median lanes decreases on the uphill section. In addition, we will show that in most cases the formation and growth of traffic flow disturbances on the center and median lanes is triggered by instabilities in car-following behavior; disruptive lane changes are a less frequent triggering factor. From those results, we conclude that changes in car-following behavior are the dominant factor reducing the capacity of the fast lane(s) at sags. The findings presented in this paper can help to develop effective measures to reduce congestion at sag sections.

The rest of this paper is structured as follows. Section 2 describes the main causes of congestion 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 methods used to identify the main factor reducing the capacity of the fast lane(s) at sags. 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 LITERATURE REVIEW ON CAUSES OF CONGESTION AT SAGS

Bottlenecks are freeway sections with a lower traffic flow capacity than the immediate upstream section; in general, when input flow exceed the capacity of a bottleneck, congestion forms on the immediate upstream section *(7)*. Several empirical studies show that capacity at sags can be significantly lower (even 30% lower) than at flat sections having the same number of lanes *(2, 3, 9)*. Because of that, sags may become bottlenecks in freeway networks, causing the formation of congestion in conditions of high traffic demand. In general, the lower part of the uphill section (i.e., first 500-1000 m after the bottom of the sag) is the main bottleneck at sags *(4)*.

The factors that reduce the capacity of the uphill section at sags have not been clearly identified yet. Several studies show that two important changes in car-following behavior occur when vehicles reach the uphill section. First, drivers tend to reduce speed *(1, 2, 4, 7)*. Second, drivers tend to keep longer distance headways than on the downhill section at similar speeds *(7, 8)*. These changes in car-following behavior seem to be unintentional *(8)*. They are mainly caused by the combination of two factors: increase in the resistance force that the engine must overcome in order to make vehicles accelerate, and insufficient acceleration operation by drivers *(2, 8)*. The two changes in car-following behavior mentioned above have important impacts on the capacity of the uphill section. First, they reduce lane capacity, causing traffic flow to become congested at lower flow rates than on the downhill section *(2, 7)*. Second, they modify the differences in traffic speed between lanes, which may induce drivers to perform a higher number of lane changes, reducing lane capacity further *(2, 4)*.

Typically, the process of congestion formation at sags has two phases. For example, at two-lane sag sections, congestion generally forms on the median (fast) lane of the uphill section, and from there it spreads to the shoulder (slow) lane *(2, 5)*. At sag sections with more than two lanes, a similar process can be observed: congestion generally forms first on the inner (fast) lanes and then it spreads to the outer (slow) lanes *(6)*. The main reason why congestion emerges first on the fast lane(s) seem to be related to the unbalanced distribution of vehicles across lanes. With high demand and uncongested traffic, flows tend to be much higher on the fast lane(s) than on the slow lane(s) *(2, 5, 10)*; therefore, flows are closer to capacity on the fast lane(s) than on the slow lane(s) *(2)*. In the second phase, congestion spreads from the fast lane(s) to the slow lane(s). This process can be described as follows. When traffic flow becomes congested on the fast lane(s), some vehicles try to migrate to the less crowded slow lane(s) in order to avoid stopping *(5, 6)*. If the flow on the slow lane(s) is sufficiently high, lane changes become disruptive. As a result, traffic flow becomes congested also on the slow lane(s). At that point, congestion spreads to all lanes, causing a significant decrease in total output flow rates and the formation of a queue upstream of the bottleneck *(2, 6)*.

In congested traffic conditions, traffic oscillations often form as a result of traffic flow perturbations *(11)*. At sags, the most frequent triggering factor for traffic oscillations seems to be related to instabilities in car-following behavior, although some oscillations form as a result of disruptive lane changes *(11)*. At other types of bottlenecks, such as merging sections, lane-changing maneuvers are the dominant triggering factor for traffic oscillations in congested traffic *(11, 12, 13)*.

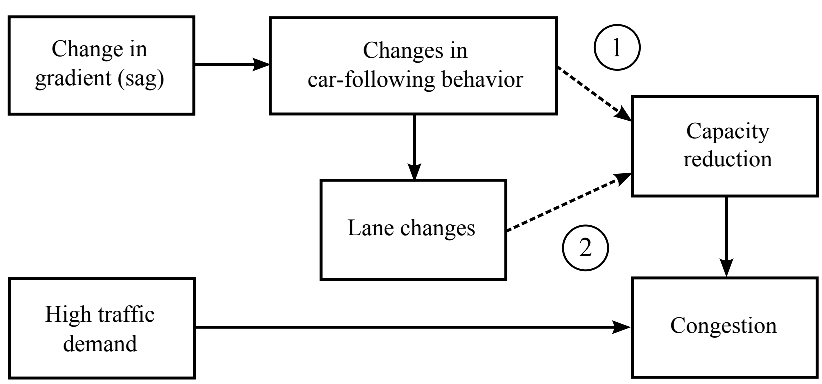


FIGURE 1 Factors reducing the capacity of the fast lane(s) on the uphill section: 1) changes in car-following behavior; and 2) disruptive lane changes.

To conclude, the scientific literature suggests that at sags congestion emerges first on the fast lane(s) of the uphill section and then it spreads to the slow lane(s). Congestion seems to spread to the slow lane(s) as a result of disruptive lane-changing maneuvers. However, the factors that trigger the formation of congestion on the fast lane(s) have not been clearly identified. Several studies show that car-following behavior changes considerably on the uphill section of sags, causing a decrease in capacity. In addition, some authors suggest that these changes in car-following behavior may cause an increase in the frequency of lane changes, reducing capacity further. However, it is not clear which of those factors is dominant or what are the causal relationships between them. The objective of this paper is to determine whether changes in car-following behavior or lane changes are the main factor reducing the capacity of the fast lane(s) at sags (see Figure 1). This is important to understand the process of traffic jam formation at sags and to design measures to effectively mitigate congestion.

3 DATA CHARACTERISTICS

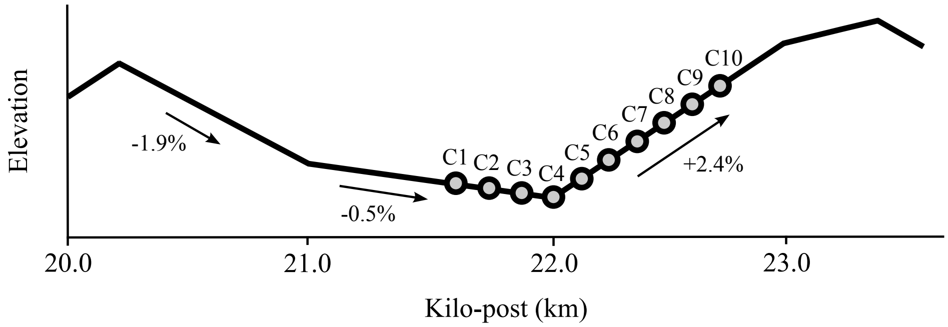
This section describes the empirical data used to analyze the factors triggering the formation of congestion at sags. The data consist of a set of vehicle trajectories on a freeway sag section in Japan during the morning peak hour. Section 3.1 describes the study site, and Section 3.2 describes the characteristics of the vehicle trajectories.

3.1 Study site

The study site is a stretch of the Tomei Expressway (near Tokyo, Japan) located between kilo-posts (KP) 20.0 and 23.5 km, going toward the West. It contains a downhill section followed by an uphill section, hence it is a sag. Figure 2a 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 2b). The median lane is the fastest and right-most lane (note that in Japan drivers drive on the left). At the study site, traffic congestion regularly forms on the uphill section without the presence of spill-back from downstream queues. However, 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. Therefore, the causes of congestion seem to be related to the site's vertical alignment profile *(6)*.

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 2a). The distance between consecutive cameras is around 120 m and the exact locations are known. Using a software tool developed by Patire *(14)*, 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 method. 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.



(a) Vertical alignment profile and camera locations.

(b) Lane layout.

FIGURE 2 Layout of the study site.

4 DATA ANALYSIS METHODS

In order to determine whether changes in car-following behavior or disruptive lane changes are the dominant factor reducing the capacity of the fast lane(s) at sags, we performed two types of analyses of microscopic flow characteristics on the study site (the variables that we analyzed are described in Section 4.1). We performed those analyses using data from the center and median lanes, which are considered to be the fast lanes of the study site. First, we analyzed the relation between average time headway and vehicle speed at different locations along the sag section. The main objective was to determine the extent to which car-following behavior changes on the uphill section, and the impact of this behavioral change on lane capacity (Section 4.2). Second, we analyzed the evolution of vehicle speed over time at all camera locations, identifying the locations where traffic flow disturbances form or grow in amplitude. Next, we analyzed individual vehicle trajectories in order to determine whether the vehicles that cause the formation or growth of disturbances decelerate due to instabilities in car-following behavior or disruptive lane changes (Section 4.3).

4.1 Calculation of microscopic flow characteristics

Calculation of time headway and speed of all vehicles at different locations along the sag section was necessary to analyze the change in the relation between headway and speed when vehicles reach the uphill section. Also, calculation of vehicle speeds was necessary to identify traffic flow disturbances and determine the locations were those disturbances form or grow in amplitude. Due to the limited space and time resolution of the trajectory data available (see Section 3.2), only average speeds between pairs of consecutive camera locations could be estimated. Gross time headways could be estimated with high accuracy, but only at camera locations.

The (gross) *time headway* of a given vehicle at a given location was calculated as the passing time of the subject vehicle minus the passing time of the previous vehicle at the same location and lane. For example, the time headway h of vehicle n at the location of camera i is:

$$h_{n,i} = t_n(x_i) - t_{n-1}(x_i). \tag{1}$$

In Equation 1: $h_{n,i}$ is the gross time headway (s) of vehicle n at the location of camera i; x_i is the location (m) of camera i; $t_n(x_i)$ is the passing time (s) at location x_i of the rear bumper of vehicle n; $t_{n-1}(x_i)$ is the passing time (s) at location x_i of the rear bumper of the previous vehicle $n-1$ driving on the same lane as vehicle n.

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

$$v_{n,i} = \frac{x_i - x_{i-1}}{t_n(x_i) - t_n(x_{i-1})}. \tag{2}$$

In Equation 2: $v_{n,i}$ is the speed (m/s) of vehicle n between the locations of cameras $i-1$ and i; x_{i-1} and x_i are the locations (m) of cameras $i-1$ and i, respectively; $t_n(x_i)$ and $t_n(x_{i-1})$ are the passing times (s) of the rear bumper of vehicle n at locations x_i and x_{i-1}, respectively.

4.2 Analysis of the relation between average time headway and vehicle speed

We examined the relation between average time headway and speed at different locations along the sag section on the center and median lanes. For each camera location i and for each lane, we followed these steps: 1) calculate the time headway ($h_{n,i}$) and speed ($v_{n,i}$) for each vehicle n; 2) distribute all vehicles in speed bins of 10 km/h (0-10, 10-20, ..., 100-110 km/h); 3) calculate the average time headway of all vehicles within each speed bin. Note that we did not estimate any function describing the relation between average time headway and vehicle speed.

Only vehicles with headways shorter than 4 seconds were included in the analysis, because above that threshold drivers cannot be assumed to be in car-following regime with sufficient certainty *(15).* Also, only the first 1200 vehicles were included in the analysis, because those are the vehicles that pass through the camera surveillance area before traffic breaks down in all lanes. The idea is to analyze car-following behavior before the occurrence of persistent congestion. Speed bins containing less than 10 vehicles at a particular location and lane were excluded from the analysis, because the average headway for those bins was considered to be unreliable due to the low number of observations. Finally, note that the relation between average time headway and speed could not be examined at the location of Camera 1, because there are no data available from any previous camera, so speeds ($v_{n,i}$) cannot be calculated.

4.3 Identification of the causes of formation and growth of speed disturbances

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 *(12).* Speed disturbances are usually triggered by traffic flow perturbations. In uncongested traffic, if a perturbation does not destabilize traffic flow, it generally propagates downstream. If a perturbation destabilizes traffic flow or traffic flow is already congested, the disturbance typically propagates upstream at a constant speed of 15-25 km/h *(16).* Sometimes speed disturbances increase or decrease in amplitude as they propagate *(12).* In order to determine the triggering factors for the formation and growth of speed disturbances propagating upstream on the fast lanes of the study site, we followed a multi-step method based on Ahn and Cassidy *(12)* (see Figure 3).

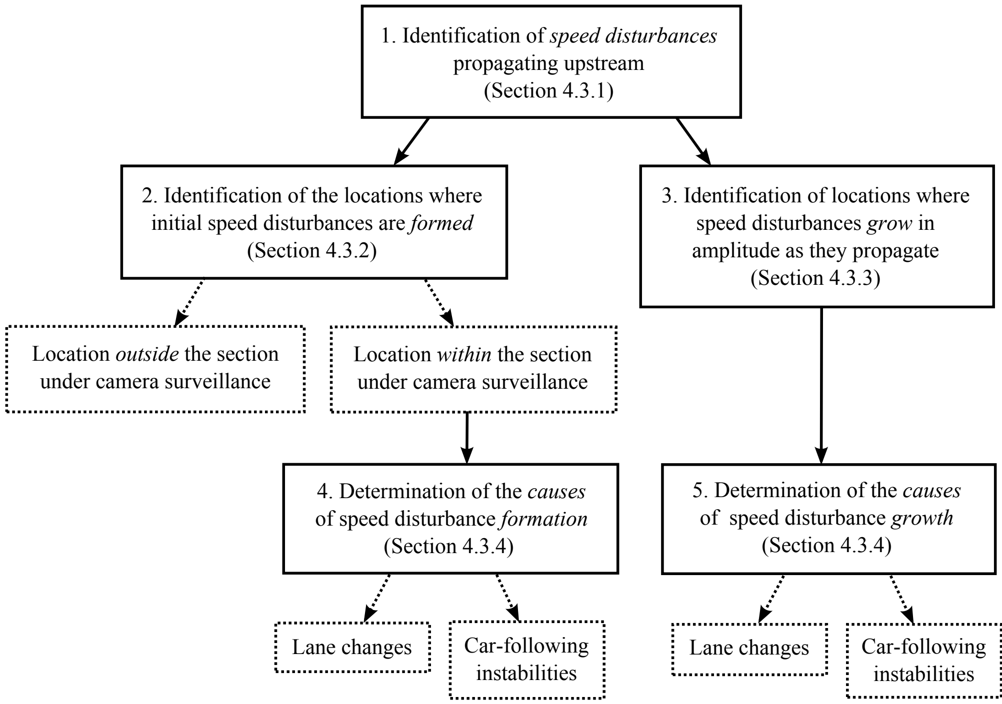


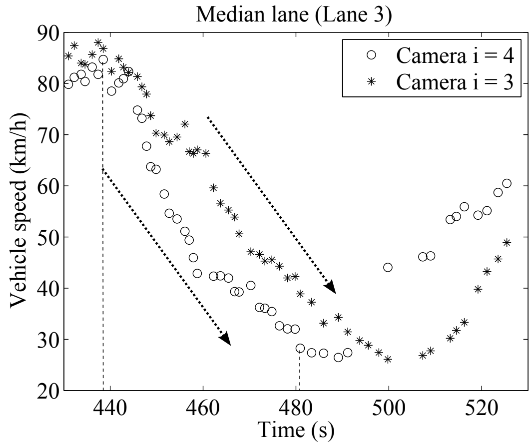
FIGURE 3 Steps to identify the causes of formation and growth of speed disturbances.

4.3.1 Identification of speed disturbances propagating upstream

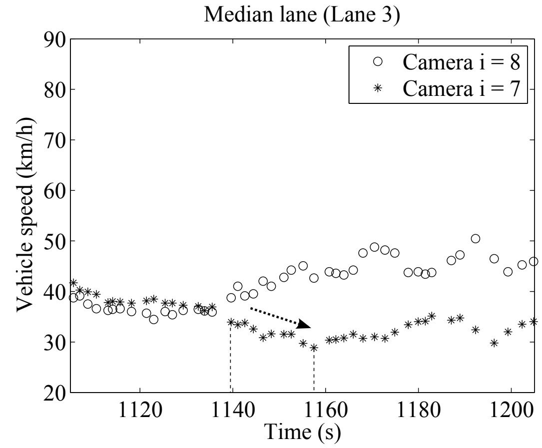
To identify the presence of speed disturbances propagating upstream, we compared the evolution of vehicle speeds over time in all pairs of consecutive camera locations. This analysis was done separately for the center and median lanes. The presence of a speed disturbance results in a rapid decrease in speed over time at a particular camera location. At the study site, the distance between consecutive video cameras is around 120 m. Therefore, if a speed disturbance propagates upstream at a wave speed of 15-25 km/h, a similar speed pattern is observed on the same lane at the next camera location in the upstream direction after 15-30 seconds. Figure 4a shows an example of speed disturbance propagating upstream. At the location of Camera 4, 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.

4.3.2 Identification of the locations where the initial speed disturbances are formed

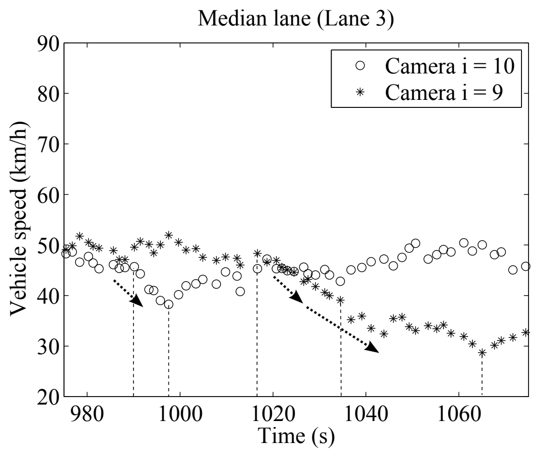
Once the presence of a speed disturbance propagating upstream was identified, we determined the location where the initial disturbance was formed (if that location is within the area under camera surveillance). At that location, speed decreases without the presence of a similar speed pattern 15-30 seconds earlier on the same lane at the previous downstream camera location. We defined that the initial speed disturbance is formed at a particular location if speed at that location reaches values more than 7 km/h lower than at the preceding downstream camera location during the previous 30 seconds *(12)*. Figure 4b shows an example of formation of initial speed disturbance, which will later propagate upstream (the latter cannot be observed in the figure). 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 speed disturbance is formed between the locations of Camera 7 and Camera 8 without the influence of any downstream trigger.



(a) Speed disturbance propagating upstream. Camera 3 is located upstream of Camera 4.



(b) Formation of an initial speed disturbance. Camera 7 is located upstream of Camera 8.

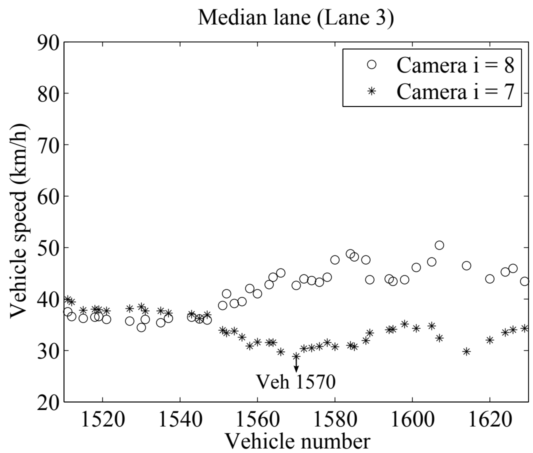


(c) Speed disturbance propagating upstream and growing in amplitude as it propagates. Camera 9 is located upstream of Camera 10.

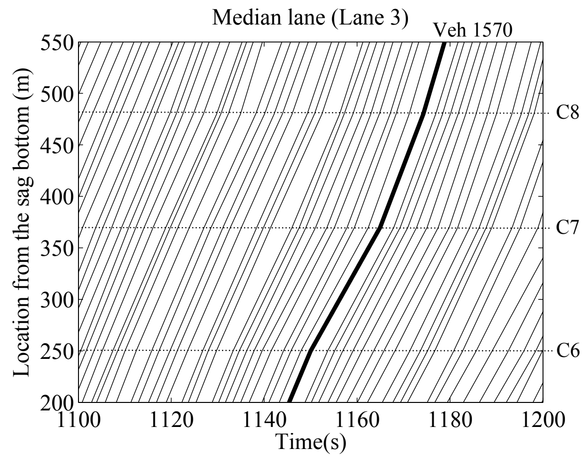
FIGURE 4 Examples of speed disturbance propagation, formation and amplification.

4.3.3 Identification of locations where speed disturbances grow in amplitude as they propagate

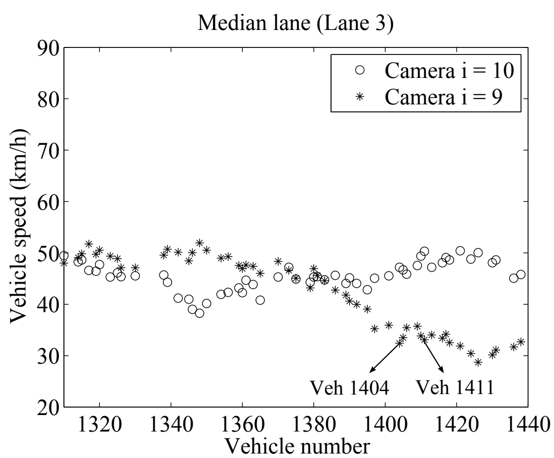
We also determined the locations within the camera surveillance area where speed disturbances grow in amplitude as they propagate upstream. The growth of a speed disturbance at a particular location results in a significantly greater decrease in speed than at the previous camera location. We defined that a disturbance grows at a particular location if the disturbance causes 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 *(12)*. Figure 4c shows an example of speed disturbance that grows as it propagates upstream. At the location of Camera 10, 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 speed disturbance grows in amplitude between the locations of Camera 9 and Camera 10.



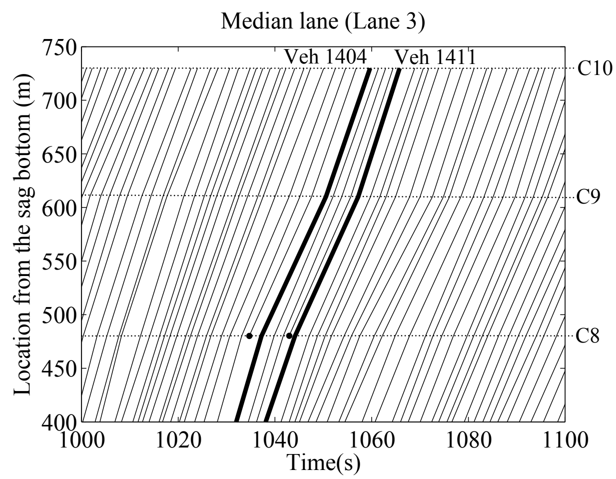
(a) Example of formation of an initial speed disturbance. Speed per vehicle number at the locations of cameras 7 and 8 on the median lane. Camera 7 is located upstream of Camera 8.



(b) Example of formation of an initial speed disturbance. Vehicle trajectories between the locations of cameras 6, 7 and 8 on the median lane.



(c) Example of speed disturbance 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 speed disturbance 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 speed disturbance formation and growth.

4.3.4 Determination of the causes of speed disturbance formation and growth

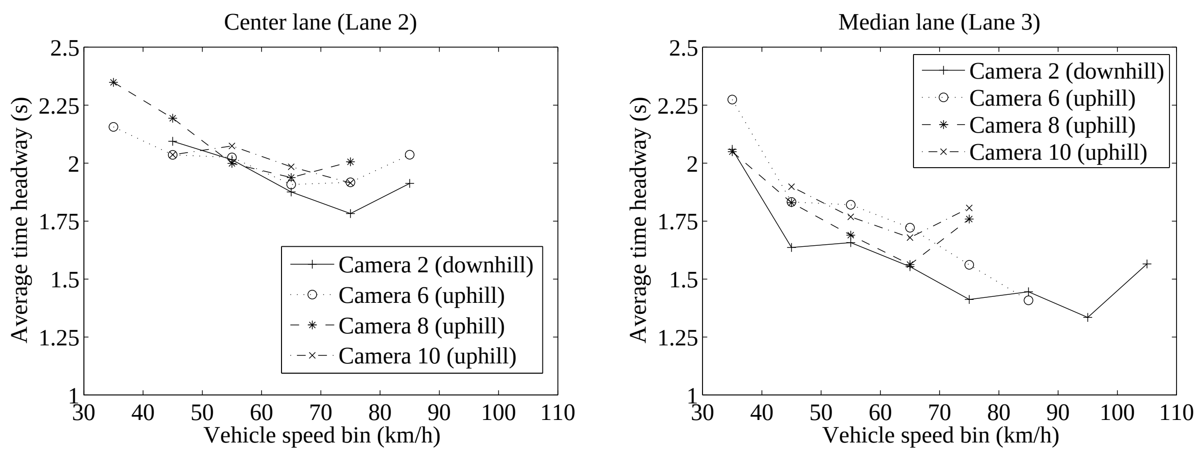
Once we identified the locations where initial speed disturbances are formed and the locations where disturbances grow as they propagate, we determined the causes why they do so. To this end, we followed a two-step approach. First we identified the vehicles that decelerate and cause the formation or growth of each disturbance. 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 5a and Figure 5c). Second, we determined the cause why those vehicles decelerate. This was done by manually analyzing 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 disturbance. If that is the case, we concluded that the cause is one or more lane-changing maneuvers (see Figure 5d). If that is not the case, we concluded that the cause is related to instabilities in car-following behavior, which may be due to the change in gradient (see Figure 5b).

5 RESULTS

This section presents the results of the analysis to identify the main factor reducing the capacity of the fast lane(s) at sags. Section 5.1 presents the results of the analysis of the relation between average headway and speed at different locations along the sag section. Section 5.2 presents the findings with regard to the causes of speed disturbance formation and growth.

5.1 Relation between average time headway and vehicle speed

Figures 6a and 6b show a comparison of the relations between average time headway and vehicle speed on the center and median lanes at the locations of Cameras 2 (downhill section), 6, 8 and 10 (uphill section). Those figures indicate that average car-following behavior changes considerably on the uphill section. Two changes can be observed. First, on average, drivers keep longer time headways on the uphill section than on the downhill approach at similar speeds. This can be observed both on the center lane (Figure 6a) and the median lane (Figure 6b). Second, on average, there is a shift in the location of the minimum value of the relation between headway and speed: the minimum headway increases and the speed corresponding to the minimum headway decreases. For instance, on the center lane, the minimums are (75 km/h, 1.78 s) at Camera 2 (downhill section) and (65 km/h, 1.94 s) at Camera 8 (uphill section) (see Figure 6a). On the median lane, the minimums are (95 km/h, 1.34 s) at Camera 2 (downhill section) and (65 km/h, 1.70 s) at Camera 10 (uphill section) (see Figure 6b).



(a) Average time headway per speed bin (center lane).

(b) Average time headway per speed bin (median lane).

FIGURE 6 Relationship between time headway and speed on the median and center lanes.

The changes in average car-following behavior described above have important effects on traffic flow capacity. The average flow is the inverse of the average time headway. Therefore, a shift in the relation between average headway and speed on the uphill section results in a change in the relation between average flow and speed. On the center lane, the increase in the minimum average time headway causes average capacity on that lane to decrease from 2000 veh/h (Camera 2, downhill section) to 1850 veh/h (Camera 8, uphill section), which represents a decrease of 8%. On the median lane, the decrease in average capacity is even higher (20%).

In order to test the statistical significance of the differences in average time headways between locations on the downhill and uphill sections, we performed several t-tests. The results show that, at the 5% significance level, the average headways on the uphill section (Cameras 6, 8 and 10) are significantly different from the average headways within the same speed bins on the downhill section (Camera 2) in four cases on the median lane. With the number of observations available, it is not possible to demonstrate that there are statistically significant differences in the average time headway for the remaining speed bins and locations on both lanes. However, in almost all cases, average time headways are greater on the uphill section locations than on the downhill section location (see Figures 6a and 6b). This seems to indicate that drivers do change their car-following behavior on the uphill section, reducing lane capacity, as suggested by other studies *(2, 7, 8)*.

5.2 Causes of formation and growth of speed disturbances

In this subsection, we present the results of the analysis of the causes of speed disturbance formation and growth on the fast lanes of the study site.

5.2.1 Speed disturbances propagating upstream

Thirteen speed disturbances propagating upstream have been identified on the center and median lanes. All of them have their origin either on the uphill section or farther downstream. Five speed disturbances propagate 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 7a and Table 1). Eight speed disturbances propagate on the median lane, of which five have their origin within the area under surveillance and the rest originate farther downstream (see Figure 7b and Table 1).

	Center lane			Median lane			Both lanes		
	Origin identified	Origin not identified	Total	Origin identified	Origin not identified	Total	Origin identified	Origin not identified	Total
Propagating disturbances	4	1	5	5	3	8	9	4	13
Cause initial disturbance (CF/LC)	3/1			5/0			8/1		
Disturbance amplifications			3			6			9
Cause amplification (CF/LC)			3/0			5/1			8/1

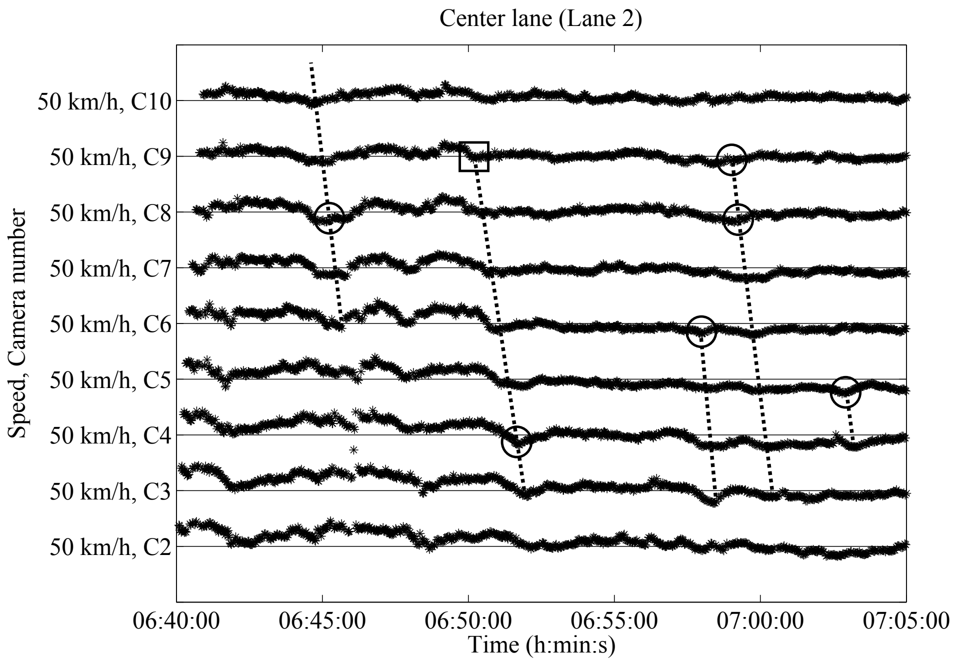
TABLE 1 Causes of formation of the initial speed disturbances causes of speed disturbance growth (CF = car-following instabilities; LC = disruptive lane changes).

5.2.2 Causes of formation of the initial speed disturbances

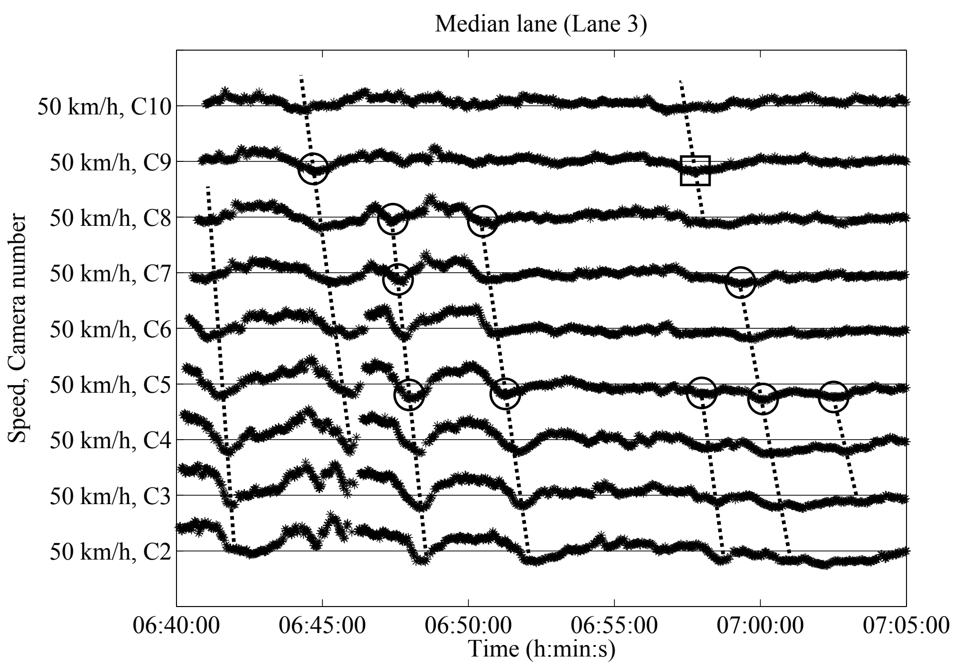
Of the nine propagating speed disturbances that have their origin within the section under camera surveillance (both in the center and median lanes), the initial speed disturbances are triggered by instabilities in car-following behavior in eight cases (see Figure 5a, Figure 5b, Figure 7a, Figure 7b and Table 1). In one case an initial speed disturbance on the center lane is triggered by lane-changing vehicles coming from the shoulder lane (see Figure 7a and Table 1). A binomial test shows that instabilities in car-following behavior are a more frequent triggering factor for the formation of the initial speed disturbances on the center and median lanes than lane changes at the 5% significance level.

5.2.3 Causes of speed disturbance growth

The thirteen propagating speed disturbances observed in the data set have been identified to grow in amplitude in nine cases. In eight of these nine cases, speed disturbances grow as a result of instabilities in car-following behavior (see Figure 7a, Figure 7b and Table 1). In one case, a speed disturbance grows on



(a) Center lane.



(b) Median lane.

FIGURE 7 Speed deviation (from 50 km/h) of vehicles passing each camera location on the center and median lanes. Dashed lines indicate the propagation of speed disturbances upstream. Circles and squares indicate locations where initial speed disturbances form or speed disturbances grow in amplitude as they propagate. Circles indicate that the cause for speed disturbance formation/amplification is related to instabilities in car-following behavior. Squares indicate that the cause for speed disturbance formation/amplification is related to disruptive lane changes.

the median lane as a result of lane-changing maneuvers performed by vehicles coming from the center lane (see Figure 5c, Figure 5d, Figure 7b and Table 1). A binomial test shows that instabilities in car-following behavior are a more frequent triggering factor for speed disturbance growth on the center and median lanes than lane changes at the 5% significance level.

6 DISCUSSION

The results presented in Section 5 must be interpreted with caution, due to the limited scope and resolution of the data.

First, we analyzed microscopic flow data of one particular sag. However, the causes of congestion are generally site-specific, therefore our findings can be generalized to other sag bottlenecks only to a certain extent. An analysis of data from additional sites is necessary to draw a final conclusion regarding the dominant factor reducing the capacity of the fast lane(s) at sags.

Second, the space and time resolution of the trajectories is limited due to the characteristics of the method used to collect the data (see Section 3.2). As a result, time headways could only be accurately estimated at a limited number of locations along the sag section, i.e. at camera locations, which are 120 m apart from each other. Also, instantaneous vehicle speeds could not be calculated; only average speeds between camera locations could be estimated. The limited number of observations and limited accuracy of speed observations reduce the level of accuracy and significance of the analysis of the relation between average headway and speed. Also, the low number of observations per vehicle makes it impossible to analyze car-following behavior of single drivers. That type of analysis could provide more insight into the impacts of sags on car-following behavior. Moreover, the limited accuracy of speed observations and the limited resolution of vehicle trajectories reduce the accuracy of the analysis of the causes of speed disturbance formation and growth. More detailed trajectory data is necessary to draw a final conclusion about the effects of changes in gradient on car-following behavior and about the causes of speed disturbance formation and growth at sags.

In spite of the data limitations, the findings presented in this study are important to understand the process of congestion formation at sags. Some studies already found evidence that car-following behavior changes on the lower part of the uphill section of sags. Drivers tend to decelerate and keep longer headways than on the downhill section at similar speeds, which has a negative effect on capacity *(2, 7, 8)*. Our results confirm that car-following behavior changes on the uphill section, reducing lane capacity. For example, at our study site, average capacity seems to decrease by 20% on the median lane of the uphill section due to changes in car-following behavior.

Furthermore, our results indicate that changes in car-following behavior are actually the most critical factor reducing the capacity of the fast lane(s), whereas lane changes are a less important factor. We found evidence that lane-changing vehicles can disrupt traffic on the fast lanes, as suggested by other authors *(2, 4)*. However, at our study site, the formation and growth of traffic flow disturbances seems to be triggered by lane changes only in a few cases (11%). In most cases (89%), disturbances form or grow as a result of instabilities in car-following behavior. This difference in frequency as triggering factor is statistically significant. From the results of our analysis, we conclude that the changes in car-following behavior that occur on the uphill section are the dominant factor reducing the capacity of the fast lane(s) at sags.

However, our conclusion does not imply that lane changes do not play a major role in the formation of persistent congestion at sags. As explained in Section 2, congestion generally forms first on the fast lane(s) of the uphill section, and from there it spreads to the slow lane(s) *(2, 5, 6)*. The findings presented in this paper suggest that the main factor causing the formation of congestion on the fast lane(s) of the uphill section is related to changes in car-following behavior. However, according to other studies, disruptive lane changes are the main factor causing the spreading of congestion to the slow lane(s) *(2, 6)*.

7 CONCLUSIONS AND OUTLOOK

Sags are frequently bottlenecks in freeway networks. With high traffic demand, congestion forms on the fast lane(s) of the uphill section and then it spreads to the slow lane(s). The literature suggests that the capacity of the fast lane(s) decreases on the uphill section due to a combination of two factors: a) changes in car-following behavior; and b) increase in the frequency of lane changes. However, it is not clear which of those two factors is dominant. The aim of this paper was to determine whether changes in car-following behavior or disruptive lane changes are the main trigger of congestion on the fast lane(s) at sags. To this end, we analyzed a set of vehicle trajectories collected by means of video cameras on a three-lane sag section of the Tomei Expressway in Japan. The center and median lane were considered to be fast lanes. We performed two types of analyses of microscopic flow characteristics. First, we analyzed the relation between average time headway and vehicle speed on the center and median lanes at different locations along the sag section. Second, we identified the causes of formation and growth of traffic flow disturbances on the center and median lanes. The results indicate that average car-following behavior changes on the uphill section of the sag of the study site. On average, drivers keep longer time headways than on the downhill section at similar speeds. As a result of these behavioral changes, the capacity of the center and median lanes decreases substantially on the uphill section. Moreover, the results indicate that the formation and growth of traffic flow disturbances on the center and median lanes is triggered in most cases by instabilities in car-following behavior; disruptive lane changes are a less frequent triggering factor. This finding suggests that changes in car-following behavior are the dominant factor reducing the capacity of the fast lane(s) at sags. However, data from additional sites and more detailed trajectory data are necessary to draw a final conclusion.

Also, further research should be aimed at thoroughly investigating the reasons why drivers change their car-following behavior at sags. Previous studies suggest that this behavioral change is related to the limited ability of drivers to accelerate sufficiently on the lower part of the uphill section *(2, 8)*. In this respect, it is important to analyze the sensitivity of car-following behavior to the degree of gradient of the downhill and uphill sections. Also, it is necessary to determine the degree of variability among drivers with regard to the magnitude of their change in car-following behavior. Variability may play a role in the process of congestion formation at sags. These analyses were not carried out in this study due to the limitations of the data available.

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