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How adaptive cruise control systems may increase congestion.

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Abstract

It is appealing to believe that adaptive cruise control (ACC) systems, the forerunner of autonomous driving systems, will provide congestion relief by allowing for more efficient driving. In the paper, we investigate this hypothesis by comparing the time safety gap of ACC systems (across manufactures) with the observed revealed safety gap of human drivers. By clustering the safety gap within a network macroscopic fundamental diagram (MFD) of a large Danish motorway in the morning peak, it is concluded that; i) human drivers maintain a significantly lower safety gap when compared to the implied average safety gap of ACC enabled cars, and ii) the lower safety gap is efficient from an MFD perspective. Hence, with the ACC technology state of today and by applying standard settings, increased use of ACC is likely to contribute to more congestion.

Introduction

Today, an increasing share of new cars are sold with adaptive cruise control (ACC) systems (Bengler et al., 2014; Wilke, 2018). It is therefore expected that by time, such systems will dominate the car fleets in most countries. While it is true that ACC systems provides features that are generally desired by car drivers, it remains a question how such systems may affect road network performance. Clearly, this depends on how they are designed but also how they are used.

In the literature there are some evidence (DeMure, 2017; Benmimoun et al. 2012) that ACC systems often maintain gab distances which are too large. This is supported in a new Danish study (Wilke, 2018) in which a group of drivers is questioned about their detailed use of ACC systems. Based on the study it is concluded that ACC systems is likely to reduce density and thereby increase congestion in the road network. Another line of research looks into the investigation of ACC and connected ACC systems (CACC) by mean of micro simulation, and presented evidence that, ACC systems may contribute to added congestion. For instance, Wall (2019) and George et al. (2019) indicated that commercial ACC systems may contribute to increasing congestion and fail to be string stable when analyzed in a simulation framework.

One of the challenges of analyzing ACC performance is that ideally, it needs to be linked to the performance of the network. As an example, it is not trivial that higher gap distances (as typically maintained by ACC systems) will result in poorer overall performance. It might be that, by maintaining higher gab distances, speed can also be higher and that the combined effect may result in a higher throughput in the transport network. While this combined system can be analyzed in simulation models, such approach require calibration as well as assumptions about parameters and model structure that can question the validity and generality of the analysis. In this paper, another less restrictive approach is taken. By analyzing the empirical network macroscopic fundamental diagram (MFD) (Geroliminis and Deganzo, 2008) for the M3 motorway around Copenhagen and explore clusters of revealed gap time and speed within the MFD, it is possible to identify network performance as a function of the observed gap time. This finding is compared to gap time ranges of ACC systems for 16 car manufactures and in particular, the inferred gap times from how these systems are used. Specifically, drivers has been asked about their use of ACC systems and if and when they alter the standard settings. This led us to investigate the following research questions:

- Is it possible that, from an MFD network performance perspective, the use of commercial ACC systems, may give rise to an efficiency loss, when compared to how human drivers behave in the network?

The contribution of the paper is that, as opposed to previous work, which has mainly looked at ACC systems from simulation perspectives, we look at the problem from an empirical MFD graph which has been revealed from real behavior in a large network.

Method and data

The analysis is based on a combined investigation of three different information sets. First, information about the usage of ACC systems from the perspective of the car driver as presented in Section 2.1. Secondly, information about the technology state of ACC systems across manufactures as presented in Section 2.2. The combination of these two elements makes it possible to estimate an implied use gap time of ACC systems. This is then combined with a third information set (to be introduced in Section 2.3), namely the observed gap times on a Danish motorway system, and how the gap time is distributed within an empirical MFD that measure network performance.

ACC systems and their use

In order to investigate how ACC systems are used, a survey among users of ACC systems are carried out (Wilke, 2018). Specifically, 828 users are asked about their use of ACC and if and to what extent they alter the standard settings. The design of the survey is inspired by Winter et al. (2017) and collect information about characteristic of the driver, type of car and the use of ACC systems in general. Table 1 summarizes selected findings.

Type of behaviour	**Share**
Have changed the standard ACC settings	10-34%
Standard settings changed to more aggressive driving	Less than 50%
Use ACC on motorways	86-88%
Experiencing lower risk when using ACC	46%
Use ACC from and to work	43%
ACC maintain longer gap distances (changed settings)	77%
ACC maintain longer gap distances (no changed of settings)	44%

Table 1: Selected summary findings from a Danish study of 828 drivers and their use of ACC systems.

The survey indicate that ACC users perceive it to be less demanding for them to travel by car when they use their ACC and that their driving is more calm, more likely to be within speed limits as well as more safe (see Table 2). As regard the gap distance to the vehicle in front, 50% of the users perceive that ACC maintain longer distance compared to their normal unsupervised driving behavior.

When driving with ACC…	**% 'agreement'**
It is less demanding for me to travel by car	72%
I can pay less attention to traffic	21%
I more often carry out other activities while driving the car (e.g. talking on the phone, checking emails, changing radio/music settings etc.)	16%
The risk of collision with the car in front is smaller	46%
It takes longer for me to brake or take over control if it becomes necessary	22%
My driving is more calm and steady	67%
I am less likely to exceed the speed limits	71%
I drive more in the right side of the motorway (DK has right side rule)	39%
I do fewer overtaking's than I otherwise would have done	40%
I stay longer in the same lane on the motorway than I otherwise would have done	46%
I maintain a longer gap to the car in front of the me	50%

Table 2: Driving experience and perceived effects on driving behavior when driving with ACC.

A majority of ACC users report that they use the ACC frequently. At least 73% state that they either use ACC every time they drive or often (refer to Table 3). The most common explanation for not using the ACC is that it is perceived to be unsuitable for the type of road or traffic condition the car is operated in. Less prominent explanations involves the desire to stay in control as driver, perceiving the ACC as troublesome to use or just forgetting switching it on.

Use frequency of ACC
Every time/trip: 29%, often: 44%, sometimes: 23%, rarely: 22%
Adjusting of factory/default setting:
Adjusted settings: 22%, to shorter gap: 11%, to longer gap: 10%

Table 3: ACC use frequency and adjustments of default settings

With respect to road types and use contexts, the ACC are used most frequent on the motorways and other main roads. On these types of roads 70-87% of ACC users apply their ACC. These findings comply well with the literature (Koglbauer et al., 2017; Nienhuis, 2009). In contrast, only 30% have used the ACC when driving in urban areas and this indicate that the road type and traffic environment is importance when deciding to use the ACC. Further to this, the use of ACC in stop-and-go traffic depends on the vehicle having automatic transmission. Among ACC users with automatic transmission 27% indicate using ACC in dense, stop-and-go traffic conditions.

Road types and use contexts for ACC use	**% using ACC**
On motorways	87%
On other main roads	70%
On curvy country roads	25%
When there are only few cars on the road	24%
In dense/stop-and-go traffic	16%
When going on vacation or on long trips	51%
For driving in urban areas	30%

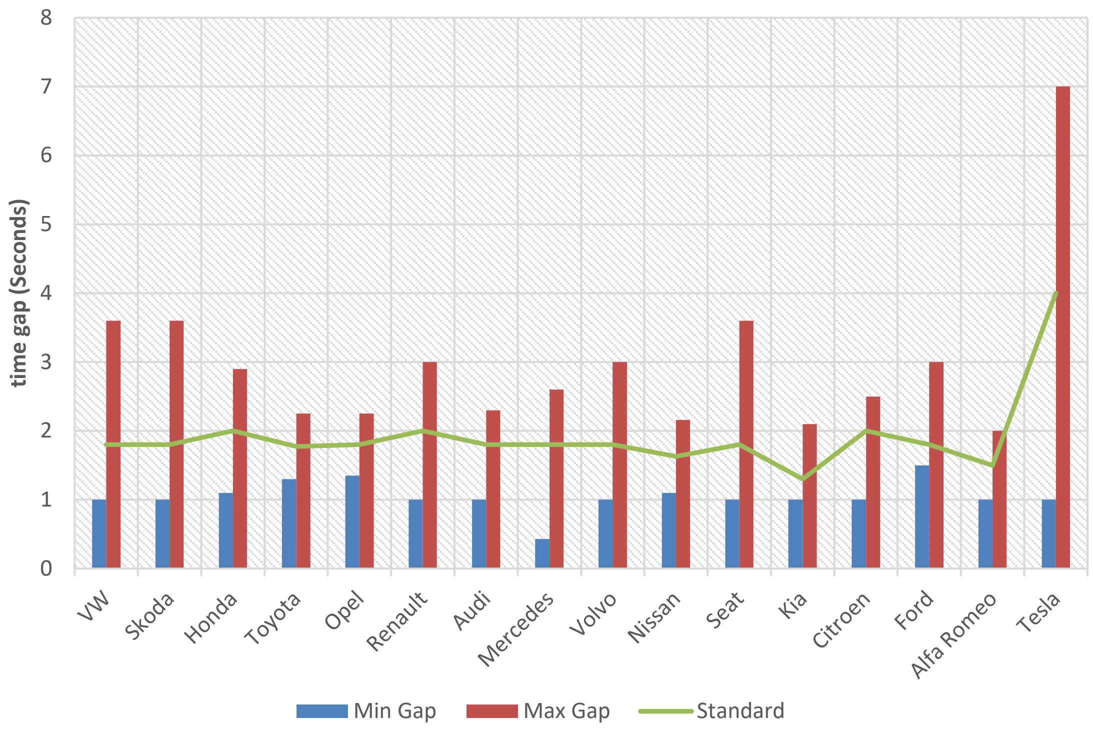
Table 4: Road types and contexts where ACC is used.

When it comes to the settings of the ACC system, the majority (78%) of the investigated drivers do not alter the standard settings, and if altered, there is no clear tendency that the system is either made more or less aggressive (Table 3). Male drivers is less risk adverse compared to female drivers. The main indication from the survey therefore, suggest that the factory and default settings of ACC systems largely define their settings in use.

ACC systems and their standard settings

While the initiated study provided information concerning the user experience and how and when standard settings is altered, the study do not provide information concerning the implied safety gaps of these systems across different car manufactures. To investigate this, ACC manuals for 16 car manufacturers are examined. This reveal minimum and maximum time gaps across brand as well as the standard setting of these systems. ACC systems differ across brands and commonly allow either 3 or 5 different settings of gap times. The average of minimum gap times across brands is slightly more than 1 second and the mean of maximum gap times is slightly less than 3 seconds. Standard settings differ as well and are in some cases the maximum gap time and in some other cases a middle position. In some cases the standard setting can be altered by the users. The ACC gap times for the different brands are presented in Figure 1 below.

Figure 2: Time gap ranges and standard settings for commercial ACC systems across brands. In some cases, it has not been



possible to identify standard settings, in these cases the figure applies a simple average between min and max.

By comparing the data from the available settings and standard settings in Figure 1, with the users stated changes to the standard settings of the ACC systems, it is revealed that the average ACC gap time is approximately 1.9 seconds across all surveyed users and brands. This is largely consistent with a study by Fridrich et al. (2015) who identified a time gap of 1.8 seconds, as well as the assumptions made by Hartmann et al. (2017) on the behavior of partially automated vehicles.

Speed and gap-time clusters in an MFD

The question now is how this average gap time of 1.9 second compares with reality and whether imposing it would lead to a degraded performance of the network. To study this we consider one of the busiest motorways around Copenhagen, the M3 motorway. In order to approximate the empirical network macroscopic flow-density relationship (Geroliminis and Deganzo, 2008), loop-detector data representing more than 6.6 Million car passages has been used. In total we have collected data for 10 different loop detectors which has been selected to avoid proximity to ramps and such that the distance between them are comparable.

Data is collected in the first two weeks (only Monday-Thursday) of September 2019. In order to avoid latent segments in the data we consider only the flow diagram of the middle lane (out of 3), the morning peak-period from 6.00 to 10.00 and south-bound traffic only. Density, flow, speed and gab times are measured for all individual cars for each of the loop-detectors. Below we present summary statistics for the selected stratification.

Period	Variables	Median	Mean	Maximum	Minimum	Std. Dev
Off peak	Density	34.9	35.9	81.1	26.4	5.0
	Speed	104.6	103.7	143.7	63.6	8.4
	Gap Time (second)	4.2	11.0	127.4	1.4	13.1
	Gap Distance (meters)	29.0	28.8	39.9	17.7	2.3
	Flow / Lane per Hour	780	819	2082	6	599
Peak	Density	58.4	59.2	170.8	34.1	19.8
	Speed	74.7	77.1	106.4	28.6	15.7
	Gap Time (second)	1.7	1.8	3.0	1.3	0.2
	Gap Distance (meters)	20.7	21.4	29.5	7.9	4.4
	Flow / Lane per Hour	1578	1568	2160	942	176

Table 5: Summary statistics for all loop-detectors on the M3, Monday-Thursday, south-bound and in the morning peak.

MFD's for highways has been considered in Cassidy et al. (2011). However, it is generally acknowledged that the fundamental diagram may be sensitive to the location of the detectors and this is also the case here. To look into this, the sensitivity of the local MFD were tested by analyzing different subsets of loop detectors. However, while the shape of the MFD changed somewhat from subset to subset, conclusions as regard optimal speed and gap time distribution, when measured inside the MFD, were stable. Hence, for the purpose of this paper, which is to provide a coarse measure of network performance as a function of the speed and the gap time, the sample of loop-detectors proved to be sufficient.

Below in Figure 2, the flow-density MDF for the system while clustering observations according to speed is shown. Flow is represented as the number of cars per lane per hour, whereas the density is the number of cars per kilometer. Both of these are 'spot-measurements' and thereby represent an approximation of the true MDF.

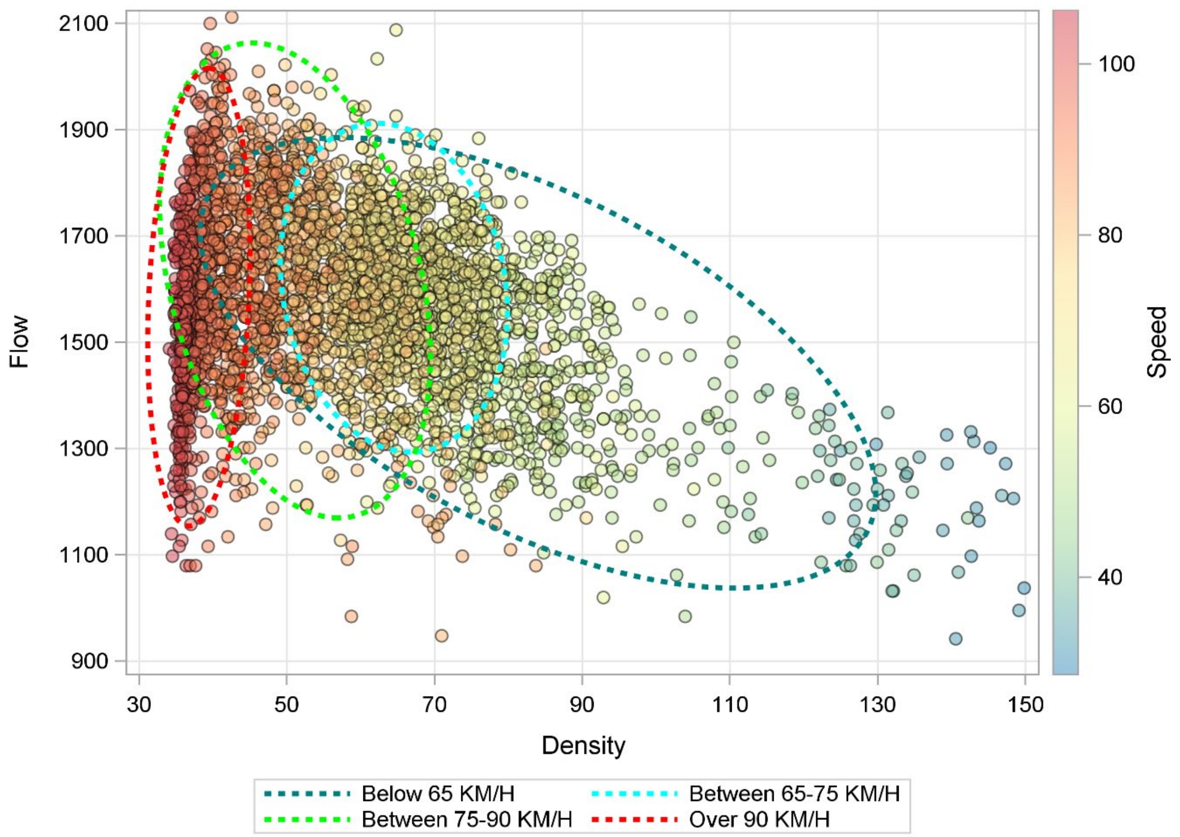


Figure 2: Flow-density MDF with speed-clusters. Flow represented as cars per hour and density as cars per KM per lane.

Not surprisingly, the cluster with the highest travel speed is observed for low densities, whereas lower speed is observed when the density increases. The optimal speed, for this system, is between 75-90 KM/H. This is the speed range where the flow is highest. Each scatter in Figure 2 represent an average measurement over 1 minutes in order to support the visual presentation of the speed clusters and reduce the number of scatters. This also makes the analysis slightly less sensitive to the number of loop detectors as the measurements represent multiple cars for each detector in time. During the analysis 5 minutes intervals were tested and it was clearly assessed that the conclusions were not affected.

In a similar manner we now turn to investigate the MFD by investigating a gap time clustering as presented in Figure 3 below. Gap time clusters are approximately defined according to quartiles. As can be seen, there is a distinct segmentation. The most effective cluster represent cars with the lowest gap time (below 1.6 second) and it is noticeable that even the 75% quartile do not surpass a gap of 1.9 seconds which is the average gap time for ACC systems as discussed in relation to Figure 1.

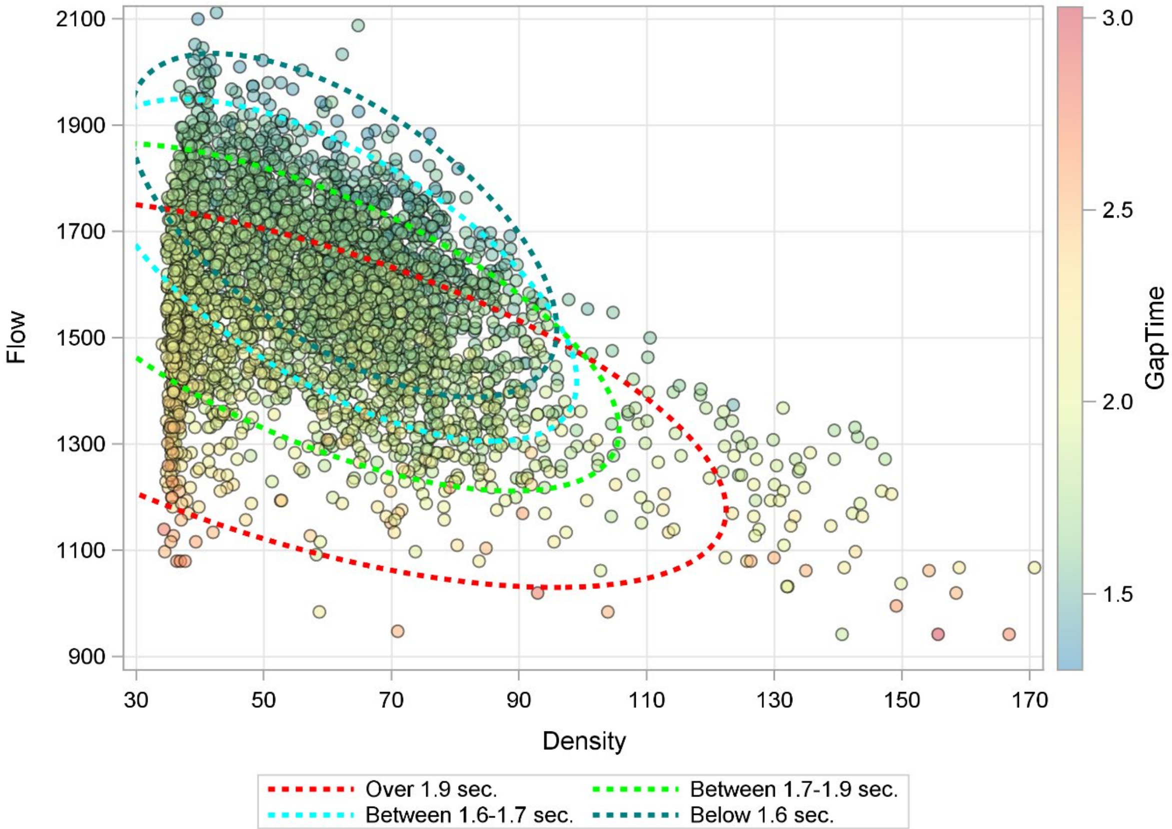


Figure 3: Flow-density MFD with gap-time clusters. Flow represented as cars per hour and density as cars per KM per lane. The 95% ellipses define the gravity of the different clusters.

Based on Figure 3 it appears that if gab times were forced to the 1.9 seconds as revealed in Figure 1, the performance of the system would degenerate significantly. If such a gap were enforced, it would lead to a percentage decrease in throughput of approximately 15-30%. An alternative presentation of the time gap MFD is in the form of a Loess regression plot as presented in Appendix A. In the plot the independent variables in the model are divided by the respective 10% trimmed standard deviations before the fitted model is computed. This take account of differences in scale between the flow and the density. Figure 6 shows very clearly how the different time gaps frontiers represent different performance regimes when measured in the MFD.

As discussed above, the form of the MFD is a function of the location of the loop detectors (Buisson and Ladier, 2009). To investigate how the presented analysis is sensitive to the location of the detectors, different local gap-time MFD's based on different sets of loop-detectors is generated. Two of these are include in the Appendix B. One set depict a regime with lower flow and a left-skewed distribution (Figure 4) while the second MFD has higher flow and a more right-skewed distribution (Figure 5). However, in both of these graphs, it is clearly illustrated how the order of the 95% ellipses representing the "gravity" of the gap time distribution is unaffected.

Summary and conclusion

The paper shed light on the possible negative consequences of ACC systems with the technology of today. We do so by combining three different sets of information. First, information regarding the use of ACC systems across a sample of 828 Danish users. Secondly, information about the technology state of ACC systems of today and their standard settings across 16 different brands. Thirdly, information about empirical gap time distributions in real networks and how these are distributed in an empirical network MFD.

Specifically, it is found that human drivers in conventional vehicles in reality maintain gab distances that are substantially lower than those represented by the standard settings of most ACC systems and that this observed behavior is more efficient from an MFD perspective when compared to that of the ACC systems. There are likely different reasons for this. On the one side, human drivers appears to be willing to take risks while driving. Some of this may be attributed to the fact that they are able to mimic connected driving by observing many cars ahead. Hence, humans learn to adapt depending on the flow and the surroundings and will in many situations drive below the recommended safety gap of 2-seconds (Highway Agency, 2014). On the other hand, ACC systems are designed with standard settings that are based on risk-averseness. Some of this may have to do with liabilities but is also linked to the fact that the current ACC technology is un-connected and does not look further ahead that the car in front.

Three precautions should be noted. First, it might be that the longer ACC gap length prevent collision and thereby counteract congestion. This is in fact quite likely and will slightly undermine the results. Benmimoun et al. (2012) suggest that ACC systems may reduce accidents by approximately 7-10%. However, it should be noted that the data presented in Figure 2 and Figure 3 represent two full weeks of data, which will involve numerous incidents. Secondly, as ACC gap-length is often calculated as a function of speed, it is possible that gap time varies with speed. However, generally speaking gap time should increase with speeds to compensate for longer breaking distances. As can be observed from Figure 2, the observed speed in the peak is generally not very low. In fact, approximately 50% of the traffic is executed above the speed of 80 KM/H (Table 5). So while there could be variations in how the different ACC systems maintain gap time at different speeds, it is not likely that this will render significant lower gap times in this case. Thirdly, when observing cars passing loop detectors, a share of these cars will use ACC systems already. If one assumes that these cars applies the standard setting of 1.9 seconds, it will affect the mean of the human drivers and the gap time of these will in fact be overestimated.

Based on the findings, and by considering the possible limitations referred to above, it is the author's assessment that the ACC performance, with the technology of today and by using standard settings, cannot parallel the average performance of human drivers in peak traffic when measured according to an MFD flow-density graph. Accordingly it can be concluded that for ACC systems of today, if used for a significant share of the operating vehicles, is likely increase congestion.

Future research

With a history of almost 30 years for ACC systems it is clear that there are multiple levels of functionality and quality as regard ACC systems in the market. There is a lack of available knowledge on how different generations of ACC systems perform in real driving conditions and what effects they have on overall system performance. Experimental evidence and user studies have indicated how connectivity can cut down reaction times (Calvert et al. 2018) and may support short gaps and dense traffic in a way that is more acceptable to users (Schladover et al. 2014). Future work should look into these aspects including the valid tests and methodologies that are required to upscale anticipated effects to a roadway or the transport system.

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Appendix A: Loess contour regression of MFD and gap-time.

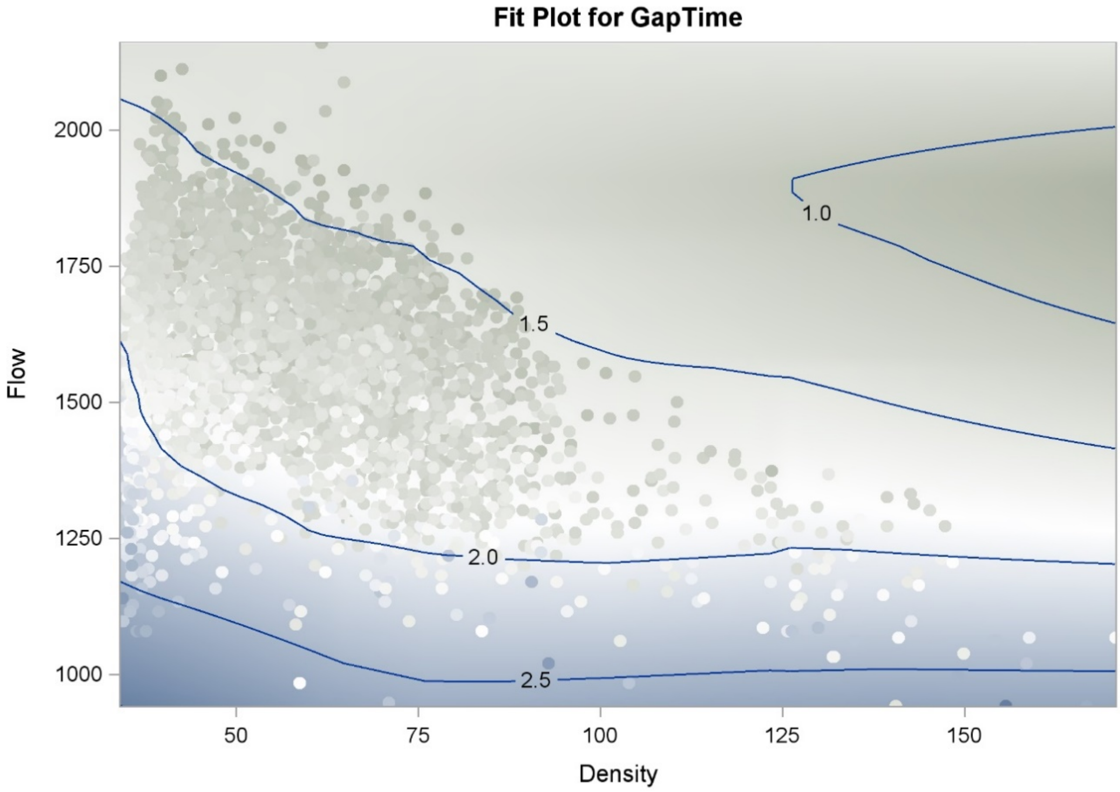

Figure 3: Loess regression contour plot for MFD with smoothed gap-time contours.

Appendix B: Variation of MFD due to location of loop-detectors

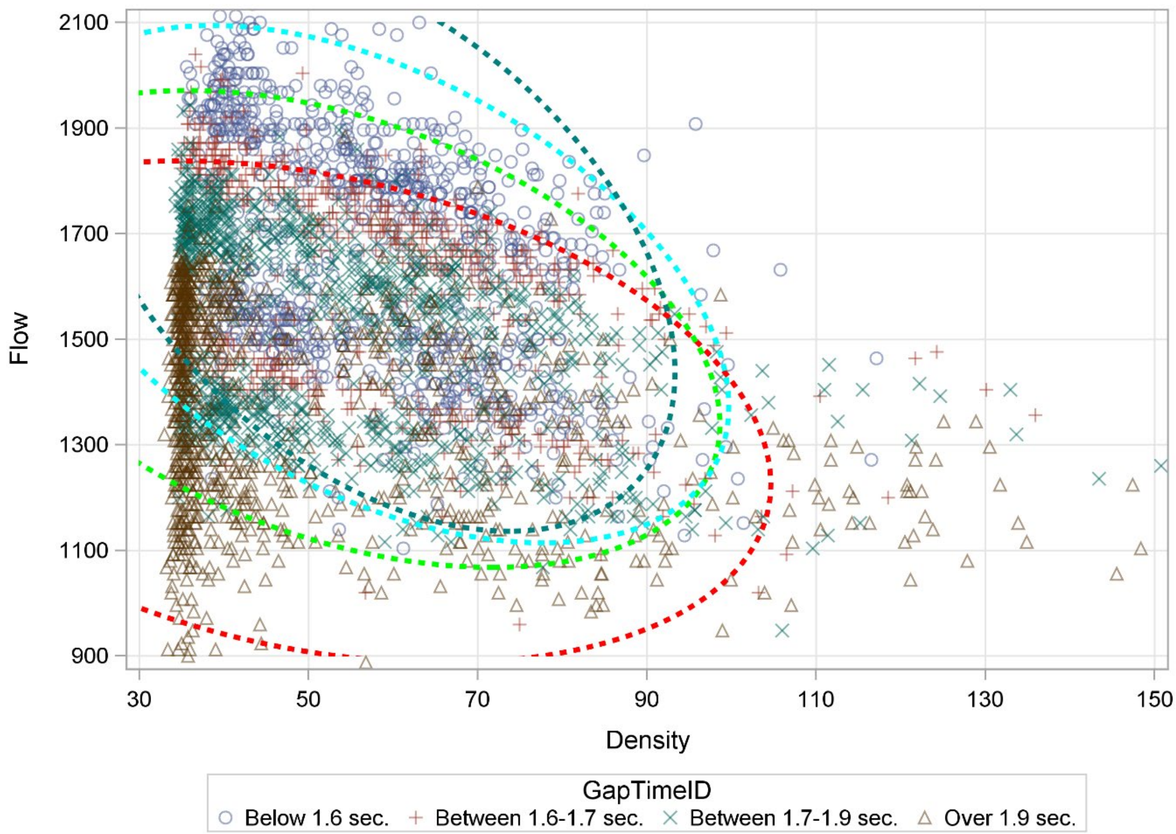

Figure 4: Flow-density MFD with gap-time clusters. Flow represented as cars per hour and density as cars per KM per lane. The 95% ellipses define the gravity of the different clusters. For loop-detector 1, 3, 5, 7 and 9.

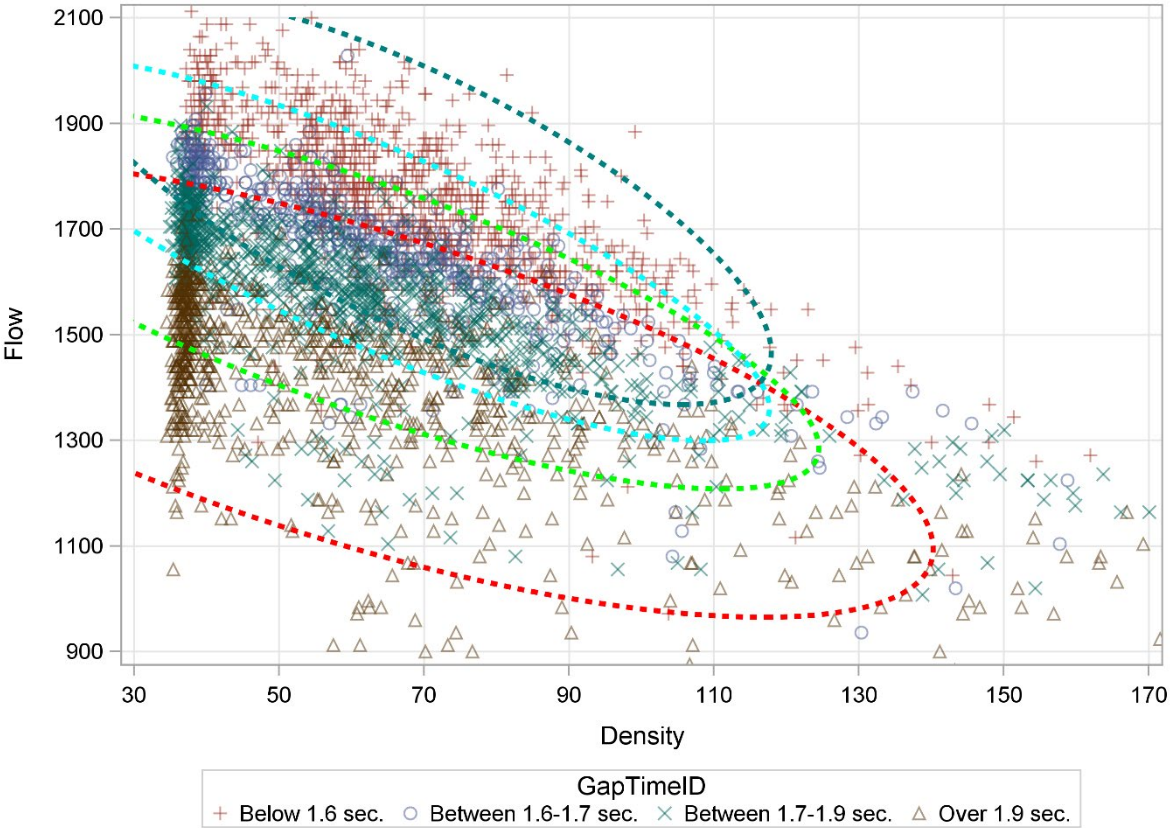

Figure 3: Flow-density MFD with gap-time clusters. Flow represented as cars per hour and density as cars per KM per lane. The 95% ellipses define the gravity of the different clusters. For loop-detector 2, 4, 6, 8 and 10.