Automating the drivers' behaviour

The use of Cooperative/Adaptive Cruise Control

By J.H. Nienhuis

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Supervisors:
B. van Arem
S. Shladover
R. Pueboobpaphan

Management summary

This report is the result of three months of research conducted at the Partners for Advanced Transit and Highways (PATH) Program of UC Berkeley. The goal was "to find relations between the usage of Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) and traffic conditions."

ACC is an advanced version of cruise control; next to a fixed speed, ACC can also set a fixed gap to the preceding vehicle. With this enhancement, the user does not have to shut down the system or change lanes when he encounters slower moving vehicles. CACC gets a wireless feed of information from the preceding vehicle, unlike ACC, which measures distances with radar. Shorter gaps can be accomplished using CACC.

Can you estimate ACC and CACC usage levels by looking at traffic conditions? Are there patterns in the systems' usage with regard to changes in traffic conditions? How do drivers use the available gap settings presented to them? Is there a noticeable difference in the drivers' usage of ACC and CACC? With answers to these questions, the impact future C/ACC systems have on the highway throughput can be better estimated. Knowing the drivers' C/ACC usage also enables better product development.

Traffic data needed for this research comes from the highway Performance Measurement System, PeMS, which gathers occupancy, flow and speed measurements from loop detectors throughout California. Furthermore, test subjects drove a vehicle that collects ACC and CACC usage data. These two sources are combined in a new database used to answer the research questions.

There is a clear pattern in the relationship between C/ACC usage and traffic speed. These two variables are related linearly, with usage levels around 20% in slow moving traffic (~10 m/s) to 80% or more when traffic is freely flowing (~30 m/s). When drivers have to decelerate from 35 m/s to 20 m/s, 80% of the users who had the system on in the first case, shut it down between 20 m/s and 25 m/s. This is a breakpoint for C/ACC usage when it comes to traffic conditions. Participants state that comfort is a major argument for deciding to deactivate the C/ACC system.

Furthermore, there is not a clear relationship between gap setting and traffic conditions. Drivers base their gap settings primarily on their own, rarely fluctuating, preferences. In 85% of the C/ACC active periods, the drivers did not change their gap. It can therefore be hypothesized that drivers choose what they like when turning the system on, and turn the system off when they are not comfortable with this initial choice. In addition, baseline drives, without C/ACC usage, show that drivers choose longer gaps in light traffic when compared to CACC and shorter gaps in dense traffic when compared to ACC. Therefore, since drivers turn off their C/ACC in dense traffic, they must be more comfortable with manual driving. Following this line of thinking, gaps that dynamically/automatically change according to traffic conditions should increase the C/ACC active percentage in dense traffic.

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1 Introduction

This bachelor thesis in civil engineering is the result of three months of work at the Partners for Advanced Transit and Highways (PATH) Program of UC Berkeley. The research conducted, between May 1 2009 and July 31 2009, focuses on the use of an intelligent transportation system (ITS) in vehicles by drivers on the road. More specific, the impact of traffic conditions on the usage of Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC).

Cruise control allows a vehicle to maintain a constant speed without the need for users' intervention. This works well with few other vehicles on the road. With the traffic as it is surrounding most cities nowadays, cruise control has to be turned off frequently. ACC, and CACC as an extension, presents the user a tool to maintain automatically a given time gap in case of a preceding vehicle. ACC and CACC regulate based on (i) a given fixed vehicle speed, from now on called "speed regulation mode", and (ii) fixed time gap, called "car following mode". Table 4 on page 24 lists the definition of these and certain other terms.

1.1 Objective

This research focuses on the drivers' usage of such a system and its relations with traffic conditions. Important questions are: "does the usage of the system reflect certain traffic states?", "do drivers have a tendency to change the usage of ACC and CACC when traffic changes?" and "what is the usage of the gap settings available, and their relationship with the traffic?" To state the conclusive goal of this research:

"To find relations between the usage of ACC and CACC and traffic conditions."

The main research question is phrased as:

"What are the relations between the usage of ACC and CACC and traffic conditions?"

Attempts to answer this question need a dataset comprising both traffic conditions and the usage of ACC and CACC during those conditions. Traffic data is available through PeMS, Performance Measurement System, an online database that contains highway traffic data from several districts in California, including the Bay Area.

Data about the usage of ACC and CACC on these highways is available from a current research at PATH. This study uses an ACC-equipped vehicle and a CACC-equipped vehicle with several participating drivers to study behaviour in terms of time gap setting choices. Computers collect data, such as speed, system's usage and location, through a data acquisition system (DAS) present on the vehicle.

1.2 Approach

The first part of this research provides the reader insight in the design goals of ACC and CACC. In addition, it states the advantages and disadvantages.

The second part of this research will discuss the synchronisation of the two sources and the further modification of the data. This modification is necessary to account for different structures in both sources and to improve accuracy. The result is a description of the output and a visualisation of the data. This visualisation shows the reader the possibilities of the dataset.

The resulting dataset serves as an input for analyses of the dataset, part three. Answering the main research question requires several methods. The results of these methods combined with analysis of what the drivers reported about the system, presents the basis for the conclusion.

2 ACC and CACC

While the rest of the report focuses on the actual usage of the system by drivers, this section means to enhance the readers' concept of both ACC and CACC in terms of design goals and achievements.

Car producers market ACC, an enhancement of cruise control, as a mean for driver's comfort [Vahidi & Eskandarian, 2003]. Thus adding this system to their vehicles potentially increases the marketability. Because it partially relieves the need for the driver to react on sudden braking by the vehicle in front, Touran [Touran et al, 1999] conclude that it also significantly reduces the probability of collision.

Apart from comfort and safety, the impact of ACC on traffic flow is a third, potential, effect. It can improve the average traffic speed and reduce the average acceleration levels. "These improvements translate to higher traffic flow rate, lower fuel consumption and smoother and safer rides." [Liang & Peng, 2000] Other studies also point at significant reductions in pollution for driving with ACC [Bose & Ioannou, 2001]. However, dangers are that a decrease in mental workload may affect the drivers' awareness of the status of the system. Stanton [Stanton et al, 1997] believes that the headway should be large enough to provide drivers with the opportunity to reclaim control in an emergency scenario. A good interface would help the driver be aware of the limitations of the system [Becker, 1996]. VanderWerf argued that a maximum of 7% increase in highway capacity could be achieved with 20 to 60% market penetration for ACC, assuming a 1.4 second preferred gap. Penetrations above 60% result in a decline in highway capacity, a gap of 1.4 seconds being longer than what manually driven vehicle's use. [VanderWerf et al, 2002] The acquired dataset for this project shows an average gap setting of 1.65 seconds. This would result in even worse performances for ACC with regard to highway capacity.

To resolve these issues, CACC is developed as an enhancement of ACC. CACC adds vehicle-to-vehicle communication to the ACC system, providing more and better information about the vehicle in front. It will therefore be "safer, smoother, and more "natural" in response" [van Arem, 2006]. ACC vehicles calculate required speed upon measured distances to the vehicle in front. This reaction time creates a lag in speed adaptations between the two vehicles. CACC gets a direct feed of information from the vehicle in front, and is therefore able to alter speed much faster. This increase in turn allows for shorter gap options in the CACC compared to the ACC. From a drivers' perspective, the faster reaction times and the availability of shorter gap settings is the main difference between CACC and ACC. For this project, the ACC system has the gap options 1.1, 1.6 and 2.2 seconds. CACC users can choose between 0.6, 0.7, 0.9 and 1.1 seconds. Note that in order for the CACC to work, a vehicle in front has to be able to send information. CACC systems in general can reach safe gaps in the range of 0.5 seconds. Thus, they are able to achieve "significant highway capacity increases" [VanderWerf et al, 2002]. This increase is only possible with a large share of CACC vehicle's on the road, because of the raised chance of available, other CACC vehicles for communication purposes [VanderWerf et al, 2002].

In 2006, 20 ACC-equipped vehicles conducted a field operational test. [Viti et al, 2008] Among other things, it found a relationship between driving conditions and ACC usage. With low to medium traffic densities, average behaviour was mainly characterised by very high ACC usages, ranging between 90% and 100%. The research also found that between densities of 20 and 40 vehicles/km/lane the drivers tended to overrule the system. The data recorded no ACC usage above 60 vehicles/km/lane. A similar test, although with a technically inferior ACC system[1], in the USA shows individual ACC usages between 20% and 100%. The average also increases with the vehicle speed. ACC usage was 50% when the cases were limited to 35 mph and above. [Fancher et al, 1998]

Overall, one can conclude that both systems are able to provide drivers with increased comfort. When it comes to improving traffic conditions, CACC is to be preferred over ACC. These improvements however depend heavily on the actual usage of system, which declines rapidly with increasing traffic density. The following chapter describes the creation of the dataset needed to research this usage and extend it to the different gap settings and CACC usage.

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[1] The ACC system used in this test was not able to brake. The vehicle used the gearing and the throttle for deceleration.

3 Generating data: C/ACC-vehicle and PeMS

This section discusses the steps involved in the synchronisation of two data sources. Chapter 3.1 describes both inputs, chapter 3.2 the method that is used and chapter 3.3 presents (a visualisation of) the output.

3.1 Input

Inherent to the goal of synchronisation is the input of multiple data sources. Subsection 3.1.1 describes source one, the C/ACC vehicle database. Subsection 3.1.2 describes the second source, PeMS.

3.1.1 Source I (C/ACC vehicle)

Task order 6202, or "Effects of cooperative adaptive cruise control on traffic flow: testing drivers' choices of following distances" is a PATH research on cooperative adaptive cruise control (CACC). The goal of the research is to acquire knowledge about drivers' behaviour regarding the usage of (the gap settings in) CACC and ACC systems and about the differences in behaviour between those two systems.

Two test vehicles collect the data, one equipped with ACC and the other with CACC. In addition, several test subjects were driving these vehicles, up to 11 on the time of writing [15 July 2009]. Each drove for two weeks, consisting of 2 baseline days, 2 CACC days and 9 ACC days. While driving CACC, the participant was following the ACC vehicle driven by a PATH employee. Appendix 10.1 contains the protocol that the drivers were required to follow, along with a timetable of the different driving days.

The working of the ACC and CACC systems is dependent on the speed of the vehicle. The table below gives the working of both ACC and CACC according to different vehicle speeds.

Table 1: The working of ACC and CACC at different vehicle speeds.

System	*Speed (m/s)*	*System capabilities*
ACC	12 and up	ACC can accelerate to the set speed and can follow preceding vehicle.
ACC	7 to 12	ACC can follow preceding vehicle but cannot return to the set speed by itself.
ACC	0 to 7	ACC is automatically turned off when the vehicle speed drops below 7 m/s.
CACC	12 and up	CACC can accelerate to the set speed and can follow preceding vehicle.
CACC	5 to 12	CACC can follow preceding vehicle but cannot return to the set speed by itself.
CACC	0 to 5	CACC is automatically turned off when the vehicle speed drops below 5 m/s.

It is important to keep the limitations of the system in mind when trying to describe the driver's behaviour.

The test vehicles record data through 3 computers. These computers are linked with several cameras, a GPS receiver and the vehicle with the C/ACC system. Location, speed, braking and C/ACC status are, among many others, recorded at 20Hz throughout the duration of the trips. The data is stored in a file on the computer every 2 minutes. Appendix 10.2 contains a list of the most important variables. After two weeks of recording, the car is returned and the data is transferred to a local computer at PATH. The car is then lent out again to a new participant.

3.1.2 Source II (PeMS)

The second source of data is the freeway Performance Measurement System (PeMS). This system is an online database containing traffic data of the last 10 years from all California. It shows the traffic flow, occupancy and, when possible, traffic speed measured directly through detector loops that are placed on the highway.

3.1.2.1 Detector loops

PeMS as a whole contains more than 26,000 detector loops divided over 8,100 detector stations. [PeMS, n.d.] These units are commonly between 500 and 800 meters apart. [Varaiya, 2001] This, however, depends a lot on the respective location. Appendix 10.3 contains a map of the placement of detector stations throughout Caltrans district 4.

The detector loops aggregate traffic measurements over usually a 30-second interval[2]. As mentioned, not all detectors in PeMS record speed, because speed has both a temporal as a spatial element. For the measurement of a spatial element, a double loop is required. Most detectors in district 4, which primarily covers the C/ACC driving area, are double loops. When the loop does not record speed, the result is a blank field in the data.

Not all detectors work every time of the day. At the time of writing, the detector health in district 4 is 59%, which means 41% of the detectors are not able to measure data due to some error. [PeMS, June 30 2009] These errors consist of a lack of data, insufficient data, errors while transferring the data and others. However, a detector health of 59% does not mean that the 59% of the stations that report data, report correct data. Several other processes described in chapter 3.2 "Method" do a further cleaning of the data.

3.1.2.2 Traffic variables

Traffic flow is provided by the number of times the detector loop changed from "off" to "on" in the 30-second interval. It can be represented therefore as a measure of the number of cars in time. The highway capacity manual [TRB, 1985] suggests using at least 15-minute intervals for a reliable sample. Wright and Lupton [Wright & Lupton, 2001] argued that too low intervals might not "provide a sufficiently large window to capture the cause-and-effect process involved". Figure 1 presents the relationship between traffic speed and different traffic flow samples.

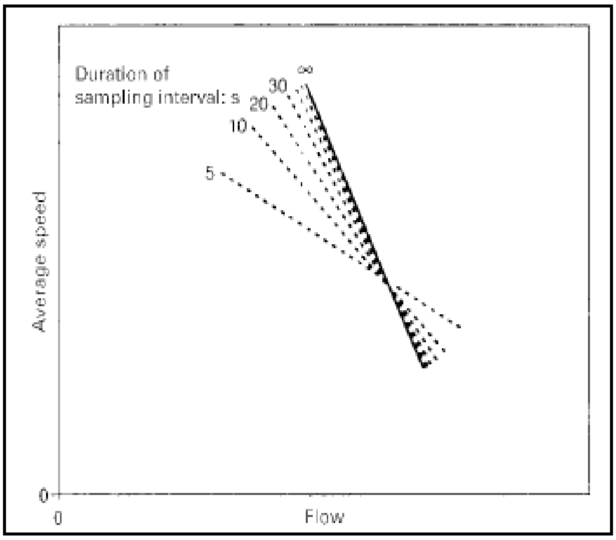

Figure 1: Effect of aggregate interval on flow accuracy [Wright and Lupton, 2001]

For microscopic analysis of the data, larger windows than the 30-second minimum could possibly not provide the desired accuracy in terms of temporal fluctuations. Therefore, the original window of 30 seconds is maintained. Traffic occupancy is measured by the total time the detector is occupied during a sample period of 30 seconds. Occupancy is frequently used as a surrogate for density measurement, which is equal to the number of cars in a space. The traffic speed is directly measured by two loops placed close to each other, also called a double loop. The distance between the two detectors divided by the difference between the two passing times of a vehicle is a close approximation of the vehicle's speed, except during rapid acceleration or deceleration. [Hall, 1992]

3.1.2.3 Data organisation

All loops present at a location, equal to the number of lanes, make a station with a unique station ID. With this number, a cross-reference between a traffic data file and a metadata file is possible. The metadata file contains current information per station such as the coordinates, freeway number,

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[2] If the respective measuring interval differs from 30 seconds, the data is adjusted proportionally.

direction and post mile. The coordinates are the basis of the link between traffic data and vehicle data. The following chapter describes how that link is constructed and how it operates.

3.2 Method

This chapter illustrates the synchronisation of the vehicle data and the PeMS data and the modification of the results.

3.2.1 Synchronisation

Figure 2 shows the different stages of this process. The first source is the vehicle data. Source 2 and 3 are the station metadata and station data, respectively. The top three boxes of Figure 2 represent these sources.

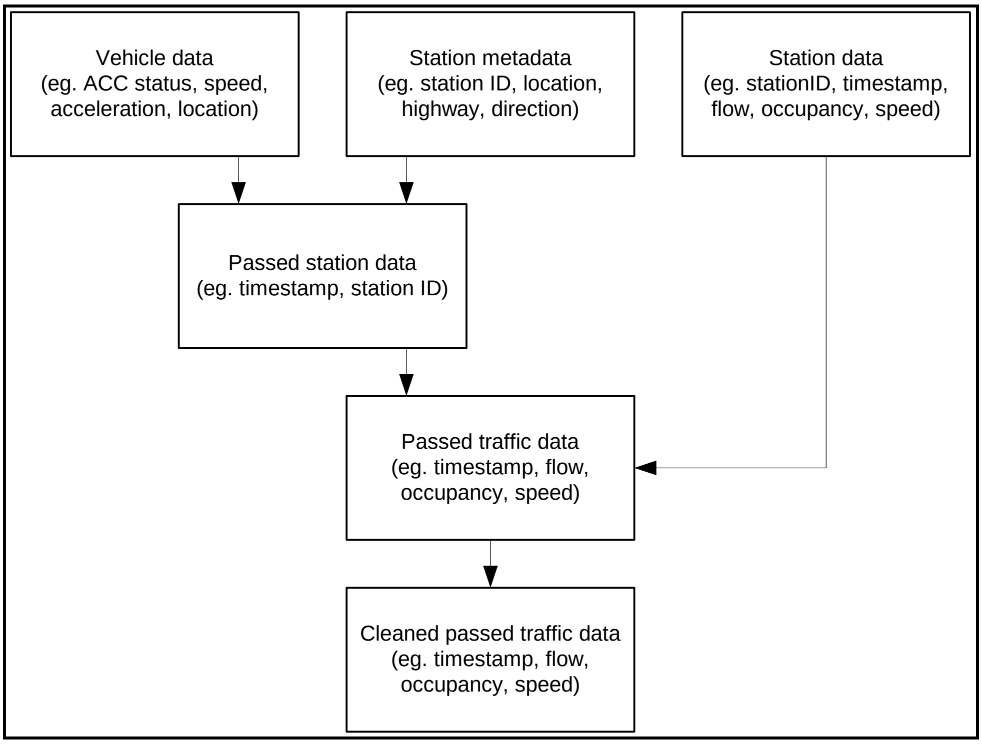

Figure 2: The synchronisation & cleaning process

3.2.1.1 Passed station data

Passed station data is created in the synchronisation of vehicle data and station metadata. For a given trip, the script loads both vehicle data and station metadata files. It then searches every entry in the station metadata coordinates and every entry in the vehicle data coordinates for matches within a 14 meters radius.[3] This resulting list contains passing time, station ID and several other location parameters.

3.2.1.2 Passed traffic data

With a list per trip from the passed station data, a script searches the actual traffic data for matches in time and station ID. These data files contain 30-second traffic data averages, resulting in almost 2 million rows per day for district 4. If the exact match is not found, the script looks for traffic data within an interval of 120 seconds around the vehicle passing time. About 0.1% of the data is not from the original, 30-second, interval. One file per trip is created and saved in the C/ACC vehicle database.

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[3] 14 meters is about the distance of going both 0.0001-degree in latitude and 0.0001-degree in longitude.

3.2.2 Data modification

The traffic data files contain errors that should be removed prior to any analysis. Table 2 lists all known errors. The script removes data with any of these errors and creates a new file with 'clean' data. Appendix 10.4 explains the arguments for excluding these values and the means of computing vehicle length.

Table 2: Errors in the traffic data[4]

Parameter	*Value*	*Occurrence (%)*	*Removal order*
Occupancy	Greater than 50%	0.3	6
Speed	Greater than 50 m/s	0.0	7
Flow	Greater than 3000 vehicles/lane/hr	0.0	5
Speed & vehicle speed	Difference more than 15 m/s	9.1	4
Stations	Not in travel direction	1.9	8
Stations	No traffic data	19.6	1
Vehicle length	Greater than 12 meters	1.8	2
Vehicle length	Less than 2.50 meters	2.0	3
Total		34.7	

Column 3 shows the percentage of the total removed data because of errors. Note that this is cumulative, so data removed because of the flow is not removed again because of the speed. Stations found in the other direction are, unlike the rest, a result of the synchronisation script and is not an error in the traffic data.

In addition, the script combines data from the different lanes to one measurement per station. There is no information about the lane on which the vehicle drove. It is possible to create a script that looks for the lane with the smallest difference between the traffic speed and the vehicle's speed. However, this research does not perform such operations because (i) it would ignore variations between lanes while these variations could help describe the traffic state [Neubert et al, 1999, p.6486] and (ii) the accuracy of the speed measurement is reduced. The traffic parameters are therefore reduced to an average over the different lanes and a single numerical description of the difference between lanes. However, the chance that the vehicle drove on a high flow lane is greater than on a low flow lane. Therefore, the weighted average of the traffic data over the traffic flow is calculated. This also improves the average speed calculation because of possible empty lanes.

3.2.3 Continuity of the traffic data

The result of the preceding scripts is a set of fragmented traffic data. One row per time the C/ACC vehicle passed a detector loop. The original vehicle data is recorded at 20Hz and can be considered continuous. Because the difference between both data sets, choices have to be made regarding the synchronisation of the two.

The result can be (i) a continuous dataset, interpolating traffic data between two nearby detector stations, or (ii) fragmented, describing vehicle data on sections with available traffic data. While (i) allows for more and diverse analyses, the choice is made to fragment the vehicle data into different sections, option (ii). The main argument is the questionable accuracy of the traffic data, especially for microscopic analysis. In 9% of the measured data, the difference between vehicle speed and "traffic speed" is more than 15 m/s. In addition, the high variability of the detector stations' locations, see appendix 10.3, makes interpolation only accurate enough on a limited amount of highways. Measuring C/ACC usage related to traffic data transitions, from one detector to another, for these limited cases, is performed in chapter 4.3.

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[4] Only 19.6% of the stations contain no traffic data. This is significantly better than the average state of the detectors throughout Caltrans district 4 on June 30, 2009.

The continuity of the vehicle data makes it possible to create a set of vehicle parameters from both before and after the time the vehicle passed the station. Paragraph 3.2.4 describes how and why that is done.

3.2.4 Further modification of the dataset

There are several advantages with the inclusion of vehicle data from around the time of passing the detector station: (i) the error in fluctuating vehicle data is limited. When the driver turned the C/ACC on for only a brief moment, exactly when the car passed the detector station, this will not greatly influence the overall C/ACC usage in a larger interval. (ii) Data is available about drivers making changes during that interval in the usage of their C/ACC system. (iii) It is possible to remove vehicle speed measurement below 7 m/s and 5 m/s for respectively the ACC vehicle and the CACC vehicle from the dataset for the entire 60-second interval. This ensures that the system did not shut down itself because of the low speed. (iv) Drivers might react on traffic conditions further up the road. See Figure 3. When the vehicle is 10 seconds before the detector loop, the driver might have turned the C/ACC system off already because of conditions reported by the detector station.

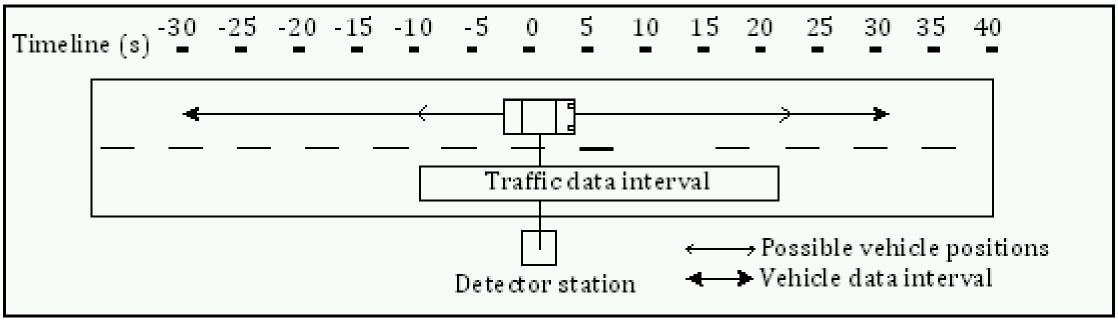

Figure 3: Temporal data intervals

Figure 3 sketches the (temporal) position of the vehicle at the time of passing the detector station. Because the traffic data consists of 30-second averages, an interval of the measured traffic is drawn. This interval can start anywhere between -29.9-seconds and 0 seconds. Note that the vehicle data interval is dependent on the vehicle's position and are not static in relation with the detector station. Appendix 10.5 states an example of this modification.

The method as described above transformed the two single sources of data into one. The following chapter describes the output.

3.3 Output

After generating and modifying the data, it can be visualised and assessed in a number of ways. Paragraph 3.3.1 describes the structure of the data. The visualisations in paragraph 3.3.2 and 3.3.3 present the reader some insight in the content.

3.3.1 Dataset

The software found an average of 17 loops with healthy data per trip. The average time between the first and the last found detector was 29.8 minutes and can be roughly classified as highway time. This means that there is an average of 1.45 minutes between two found detector loops. Figure 4 shows the distribution of the times and distances between 2 consecutive healthy and passed detector loops.

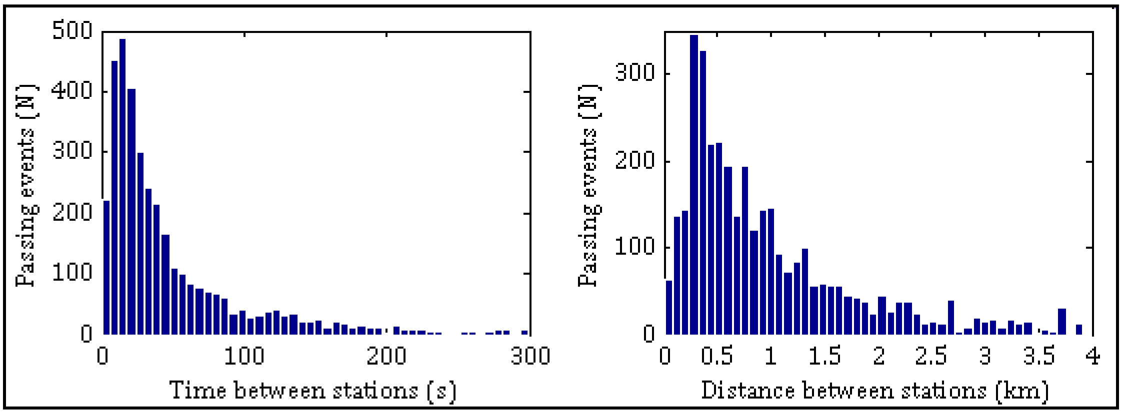

Figure 4: Distribution of "between times and distances".[5]

Next to the placement of the stations, there is also a high variability between the vehicle speed and the traffic speed and the traffic speed across different lanes. Figure 5 shows these differences in a histogram. The lines represent the distribution of the standard deviations of (i) the different lanes on one detector station and (ii) the traffic speed and the vehicle speed.

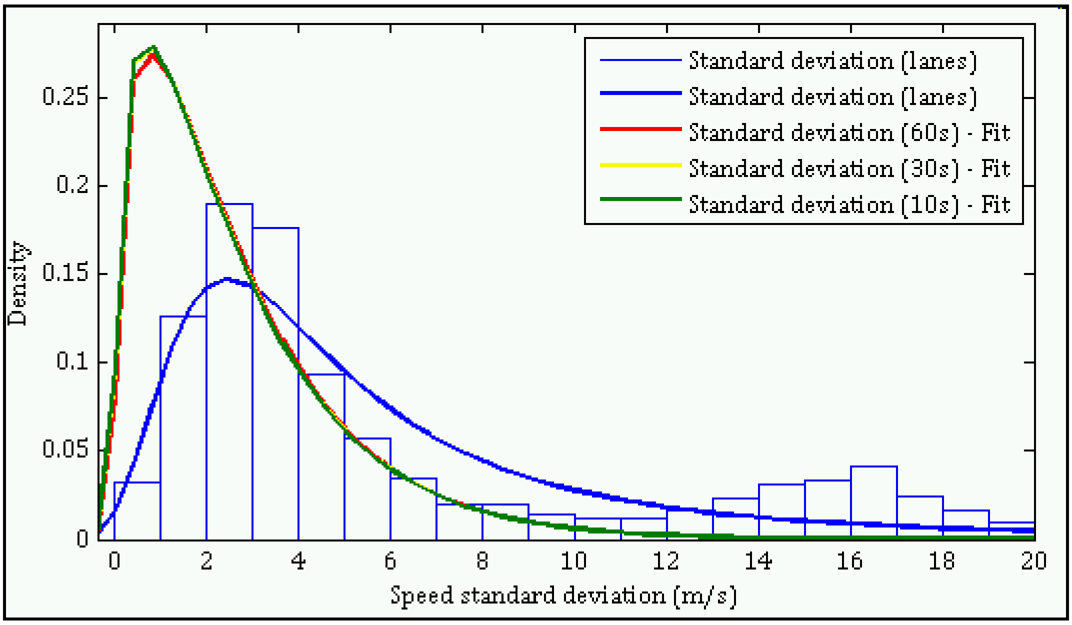

Figure 5: Standard deviation of speed between lanes and between vehicle and traffic.

"Standard deviation (number)" states the standard deviation between the average traffic speed and the average vehicle speed over an interval of "number" seconds. The very small differences between these 3 distributions show a neglectable influence of the temporal fluctuations of traffic on the speed difference between the average traffic and the vehicle. The major cause of traffic moving in a different pace than the C/ACC vehicle is however the difference between lanes. The histogram shows the standard deviation on a highway between lanes in the same figure. Interesting is large sample of speed differences at around 15 m/s. The presence of HOV (high occupancy vehicle)-lanes, also known as carpool lanes, could be responsible for this difference.

Differences between the speed of an individual vehicle and the traffic in general, and with that new information, are the main reason for combining the traffic data with the C/ACC vehicle data.

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[5] "Between times and distances" greater than 300 seconds (6% of the samples) or 4 kilometers (7% of the samples) are not displayed.

Fluctuations between lanes and temporal fluctuations on a lane could describe a traffic state better than an individual vehicle. The following subsection will provide a microscopic visualisation of the traffic conditions along a single trip.

3.3.2 Microscopic visualisation

Figure 6 presents a plot usable for microscopic data analysis.

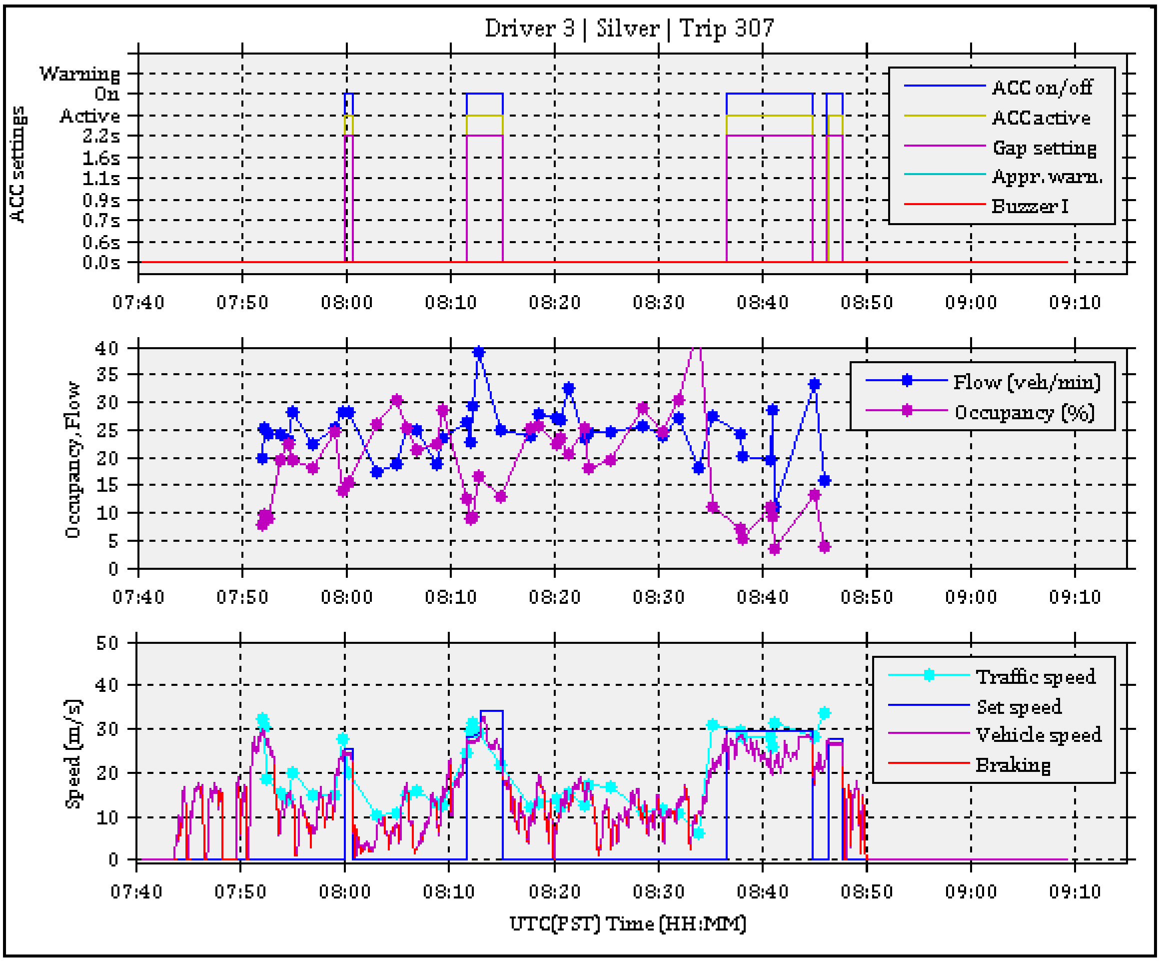

Figure 6: Details of trip 307

This graph represents trip 307 of driver 3 in the silver (ACC) vehicle. The top plot shows 4 activations and deactivations of the ACC during the trip. The gap setting stayed at 2.2 seconds, the default and starting value, the whole time. In addition, no approach warnings or other warnings are given. The middle plot displays flow and occupancy of the traffic during the trip. Every dot represents a passed station, 41 for this trip, and every line a linear interpolation between two stations.[6] A good way to interpret these values is to look for inversely proportional segments, e.g. if occupancy gets higher and flow gets lower, there is a good chance of congestion.

The bottom plot shows speed related variables. Traffic speed is, as flow and occupancy, limited to 41 points of measurement. Interesting to notice is the relationship between the speed and ACC usage, the moments in which there is a speed set by the system. There is no ACC usage below 25 m/s. In addition, the driver did not use the system to do the acceleration. Note that the system shuts down below 7 m/s for the silver car. Some of the "turning off"-events might therefore be caused by the ACC system or by the driver anticipating on that system.

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[6] The interpolation, e.g. the lines, is merely used to see the chronological order of the measurements.

Around 8:40, there is a moment in which the ACC system followed the preceding vehicle, because the actual vehicle speed is lower than the set speed.

This method allows for very accurate analysis, but is not practical for large amounts of data. The following paragraph will show another way of visualising data, namely macroscopically.

3.3.3 Macroscopic visualisation

In this macroscopic visualisation, the data from all passed detectors from all trips are combined in the fundamental diagram of traffic flow, Figure 7. This diagram plots flow versus occupancy, of which the interpretation is as the annotation in the graph. [Agyemang-Duah & Hall, 1991] For this plot, all ACC and CACC drives are included. The vehicle speeds below 7 m/s are excluded.

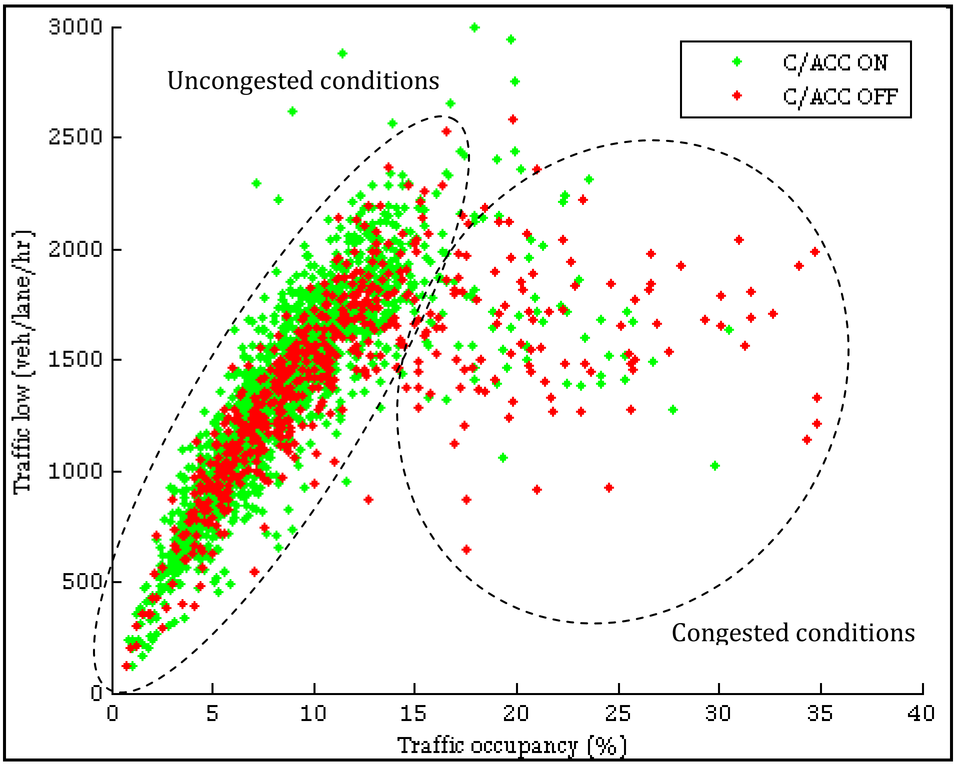

Figure 7: C/ACC usage under different traffic conditions.

There is a clear reduction of C/ACC usage in more congested traffic. However, uncongested conditions have both C/ACC on and off regularly. Very congested areas on the right of the graph also have some C/ACC usage.

Using these visualisations and other, several types of analyses are possible with this combination of C/ACC data and traffic data. The next chapter performs some of those analyses.

4 Analysing data: Drivers' use of C/ACC

As shown in the last chapter, several types of analyses are possible with the combination of C/ACC data and traffic data. One type of analysis is looking at average C/ACC usage or gap setting behaviour related to the traffic conditions, chapter 4.1 and 4.2. Extrapolating this to larger number of C/ACC users on the highway, it can give good predictions of the total amount of users under different conditions. In addition, one can look at the effect of traffic conditions transitions in the usage of C/ACC, chapter 4.3. To conclude the analysis, the findings are compared with the results of the questionnaires the participants filled in.

4.1 C/ACC usage related to traffic conditions

This analysis will try to see if the observations from earlier researches are in line with this data. In addition, the dataset is divided into several layers to learn the underlying reasons for the C/ACC usage. Paragraph 4.1.2 shows C/ACC usage in general. Paragraph 4.1.3 and 4.1.4 divide this into respectively usage between ACC and CACC and between drivers.

4.1.1 Initial observations

When a point represents an individual passing event of the vehicle over a detector loop, a scatter diagram of traffic conditions can present information of C/ACC usage in those conditions. Figure 8 shows such a plot.

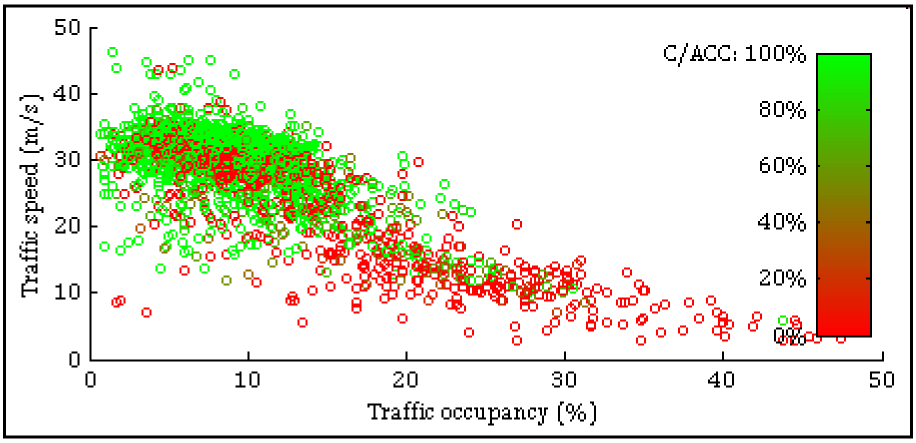

Figure 8: C/ACC usage during the 60-second interval in reported traffic conditions.

This figure shows average C/ACC usage during the 60-second interval. By far most of the data is available from free flow conditions, with speeds around 30 m/s and occupancy between 5 and 10 percent. With regard to the C/ACC usage: in the free flow period, drivers choose both 'on' and 'off' regularly. When driving speeds are limited to 20 m/s, a clear reduction in C/ACC usage is visible.

This visualisation method reveals however, much noise, mainly caused by differences in (commutes of) drivers and inaccuracies in the traffic data. Because analysing all passing events individually does not allow for good, numerical analysis, the next paragraph will aggregate over different traffic condition intervals and visualise general trends in the dataset.

4.1.2 Trends in C/ACC usage

Figure 9 shows the average C/ACC usage of the drivers while they were in traffic in that interval. The dotted lines represent a 95% confidence interval, after a method described by David Lane of Rice University. [Lane et al, 2006] This interval depends mainly on the number of data points, passing-events, available.

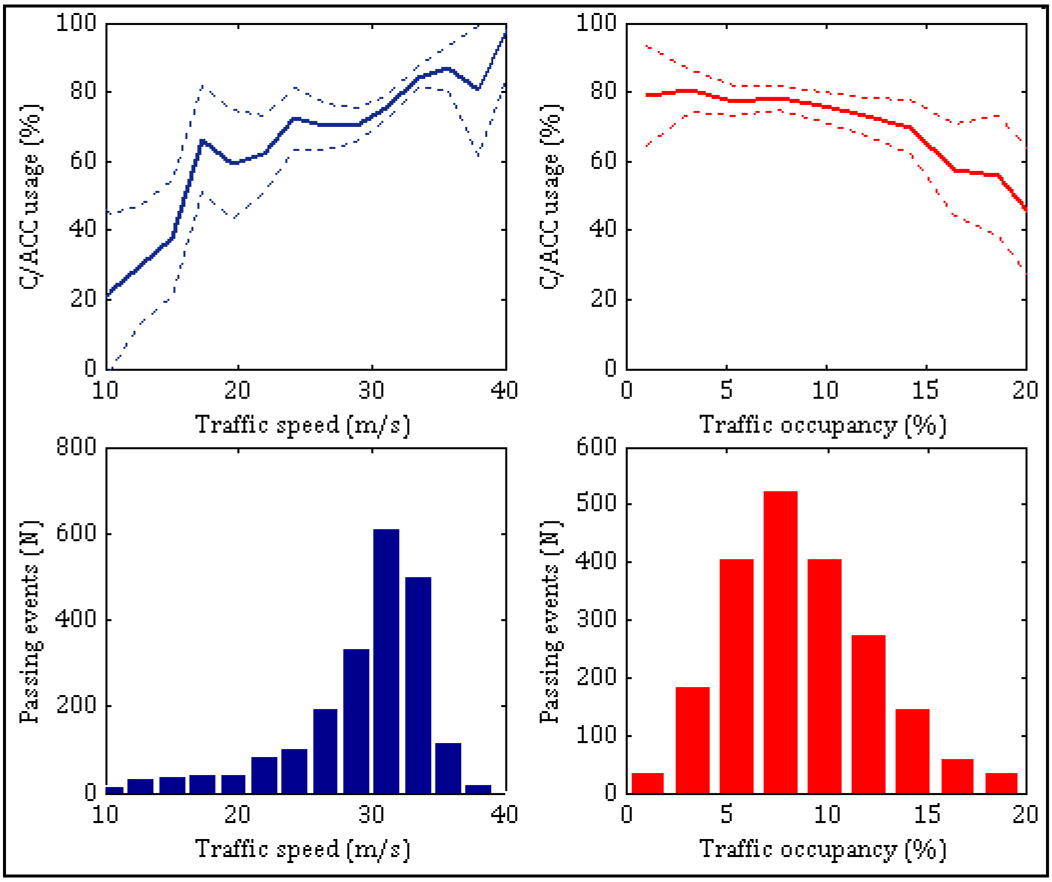

Figure 9: Relations between traffic conditions and C/ACC usage

Trends of C/ACC usage in different traffic speeds and different traffic occupancies are clearly visible. In light traffic, participants drove with their C/ACC system activated around 80% of the time. This usage drops back to around 20% to 40% in cases with congestion.

It is possible that it reduces even further with speeds lower than 10 m/s or occupancies higher than 20%. The availability of the data makes it impossible to analyse behaviour in those conditions. Figure 9.c & d show the distribution of the respectively the traffic speed and the traffic occupancy measurements. Note that the figure does not show speeds above 40 m/s because of questionable accuracy due to the available data. Interesting is the supposed usages of full range C/ACC in stop-and-go traffic. Extrapolating the line on Figure 9.a & b would mean almost no usage in those conditions. However, there is an unknown effect of this C/ACC system on drivers while the vehicle drives close to 5 m/s, its limit. Assuming no such effect at speeds higher than 10 m/s means no advantage of a full-range C/ACC over this present system. This report shall not make that assumption.

4.1.3 Trends in ACC and CACC

Assuming the ability of these parameters to estimate traffic, one would expect a clear breaking point of C/ACC usage between two distinct conditions. The linear trend, visible in Figure 9.a & b, would mean the situations on which users tend to turn off their C/ACC depends on different factors next to the traffic conditions alone, such as the respective driver, ACC or CACC etc. A multivariate analysis of variance conducted on the available variables reported significant differences in C/ACC usage dependent on both the different drivers and the different systems (ACC and CACC). Appendix 10.9 contains a full output of this analysis.[7]

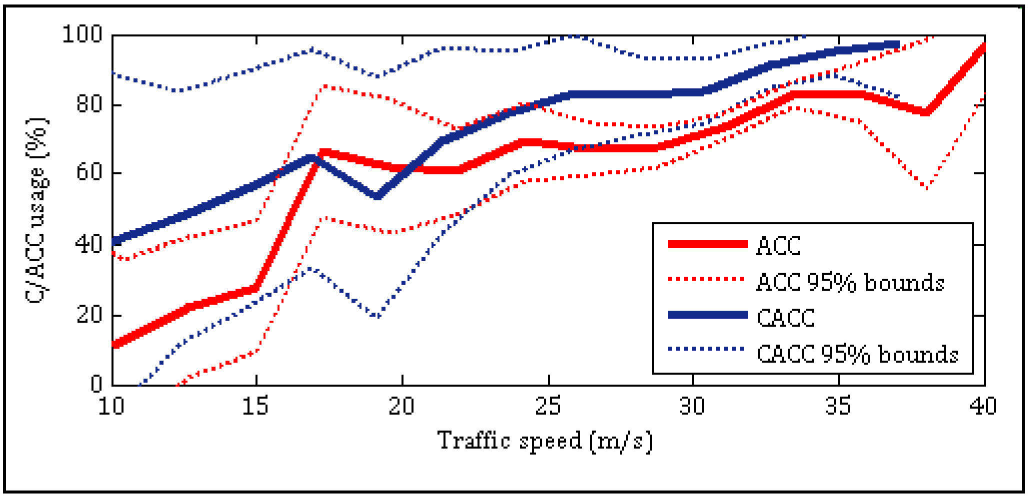

Figure 10: Differences between ACC and CACC usage

Figure 10 presents the difference between ACC and CACC in traffic conditions. While CACC shows a linear relationship with the traffic speed, average ACC usage decreases 67% between traffic speeds of 15 m/s and 17 m/s. This could be a breakpoint for most users regarding the usage of the system. However, CACC does not show such a 'breakpoint'. Furthermore, the limitations in the data cause a very broad 95% confidence zone. In fact, there is a significant difference in ACC and CACC at only a few traffic conditions.

CACC usage at around 33 m/s is higher than ACC usage at that speed, for which there are several possible causes. (i) The protocol, as described in appendix 10.1, shows that drivers had several driving days of ACC before driving the CACC vehicle. Therefore, higher usage could be because of a learning (or comfort) curve. There is however no increase in the average C/ACC usage over the two week period in which the participant drove the vehicle, see appendix 10.7. (ii) A PATH employee had to be in the passenger's seat next to the driver while driving a CACC trip. This might influence the overall usage of the system. (iii) The drivers had new gap settings to experiment while driving CACC. (iv) Due to the nature of CACC, the drivers had to follow the ACC vehicle throughout the trip. In addition, the gap settings on the CACC make the risk of cut-ins very small. This can make the CACC more comfortable and less dependent on the traffic conditions. (v) CACC can be more comfortable than ACC. There is no definitive quantitative conclusion regarding the likelihood of these explanations. But because of inaccuracies in the data, it is also both possible that CACC and ACC result in the same behaviour and that CACC does not have any relationship with the traffic conditions.

4.1.4 Trends in drivers

Figure 11 shows the difference in C/ACC usage between drivers in a boxplot. The black dot represents the average C/ACC usage over all trips of the driver. The blue line presents the difference between the first and the third quartile of the usage. The red line is the 95% data-interval and the blue circles are outliers.

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[7] These figures present only traffic speed as "condition"-variable. While the statistical test showed multiple traffic variables as having a statistical significant impact on the systems' usage, traffic speed shows most clear relationship. Furthermore, it is an easy, recognisable variable with linear effect on traffic conditions. A combined occupancy-speed-variable would possibly be a better estimator, but is not user-friendly.

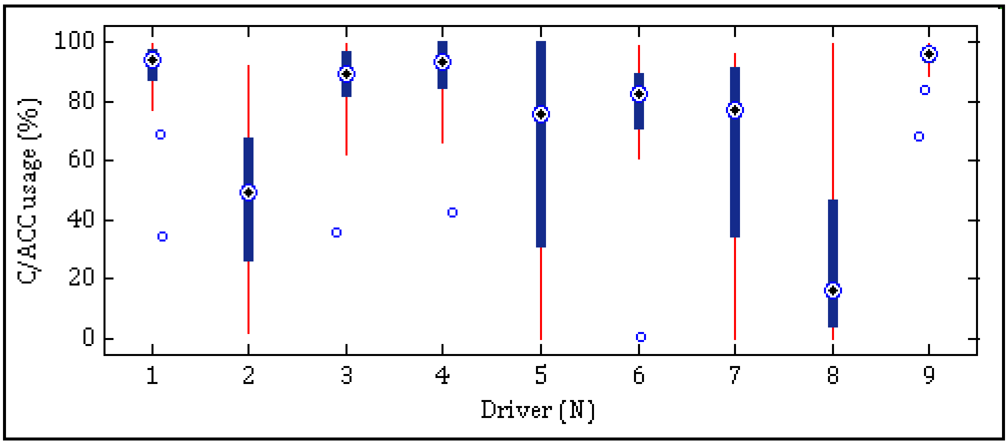

Figure 11: Average and variation of C/ACC usage on a per trip basis

Note the small variation in the different maxima. All drivers had some trips with more than 80% C/ACC usage. When it comes to minima, drivers 1, 3, 4 and 9 show that the average is dependent on the minimum usage. The small overall difference, or the high variability between trips of the same driver, makes it difficult to see a clear pattern in different reactions to traffic conditions (Figure 12).

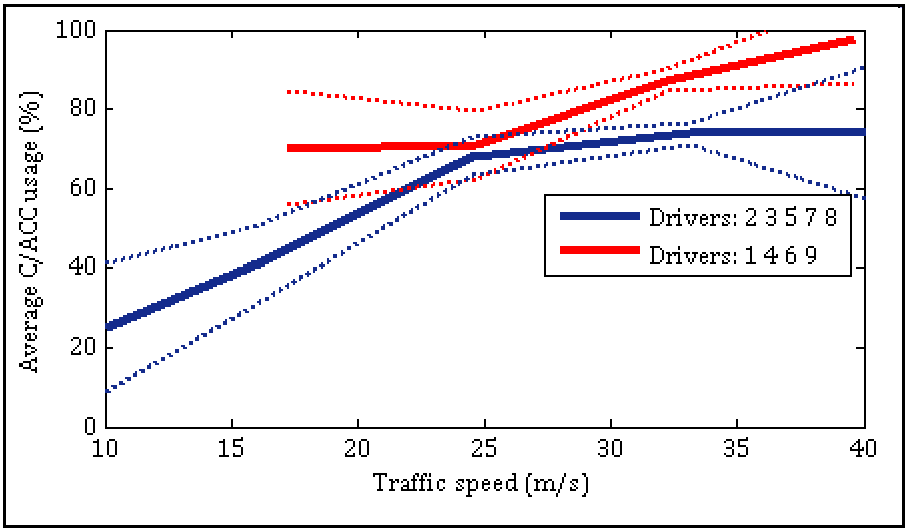

Figure 12: C/ACC by different drivers with 95% confidence interval

Figure 12 shows C/ACC usage by different groups of drivers. Note that because of limitations in the data, not a complete range is available per driver. Therefore, the graph shows data into two different groups, chosen to present the largest possible difference in the behaviour of users with respect to the traffic conditions.

Interesting to see is not only the difference in average usage, but also the different reactions of the drivers on the traffic conditions. Group 'blue' gradually increases C/ACC usage from 10 m/s to 25 m/s, with a maximum average usage of 70%. Group 'red' uses the system at about 70%, and increases it when obtaining speeds above 25 m/s.

This concludes the description of trends in C/ACC usage. Interesting observations are the clear overall pattern in C/ACC usage and traffic conditions. However, dividing this observation into groups of either the systems or the drivers does not create a clear pattern, perhaps because of minimal impact or the limitations of the dataset. Several hypotheses are given for differences between ACC and CACC. Further causes for differences per driver or system could be because of the chosen gap settings, analysed in the next chapter.

4.2 Gap setting usage in traffic conditions

Drivers in the ACC system can choose between 1.1, 1.6 and 2.2 seconds; in the CACC system, people can choose between 0.6, 0.7,0.9 and 1.1 seconds. The choice in gap settings may be highly dependent on two distinct uses of C/ACC. (i) Speed regulation mode and (ii) car following mode. Note that only in case (ii) the driver actively experiences the gap setting. Figures and graphs in this analysis will be based on only the second usage. Since the computer does not store a single variable to make a distinction between (i) and (ii), several assumptions lie behind the partition. Appendix 10.8 contains the method and the results of this partition.

4.2.1 Gap settings in ACC

Figure 13 contains a plot of the chosen gap setting relative to the traffic conditions for the ACC system.

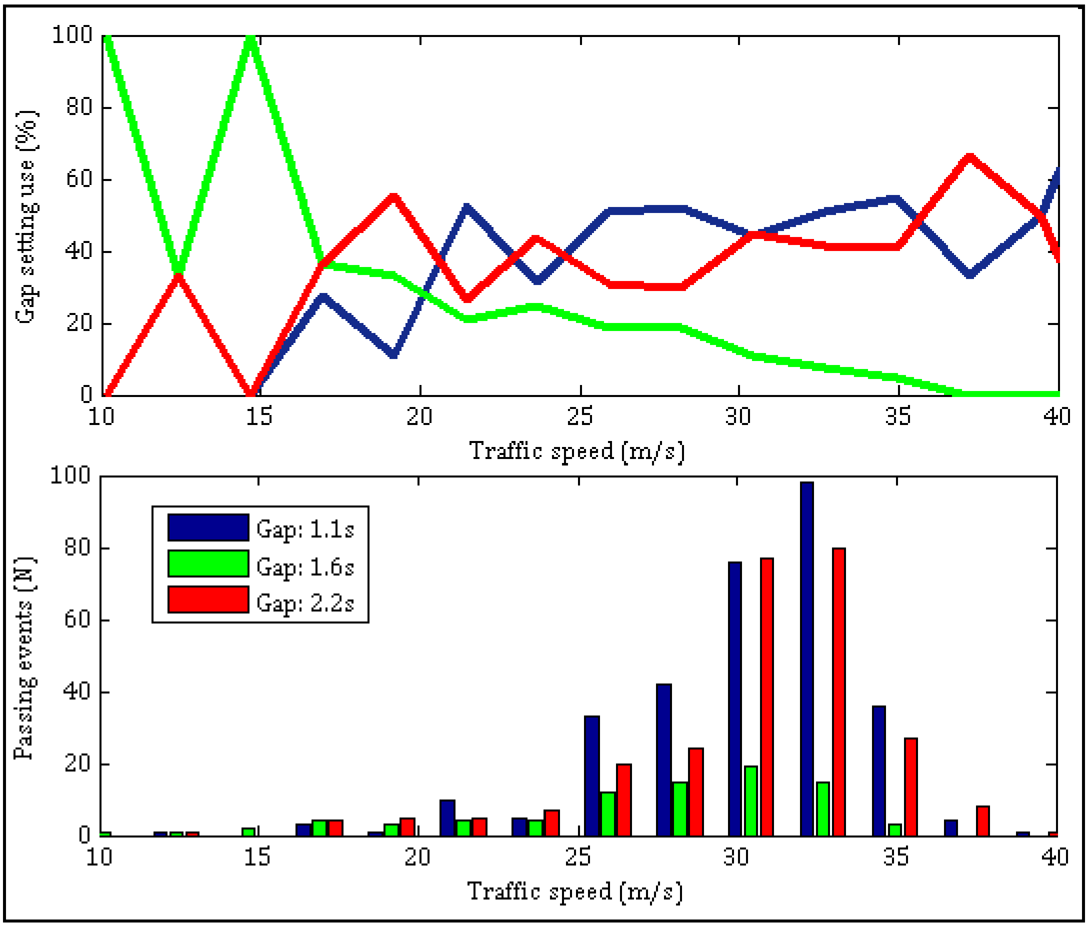

Figure 13: Gap setting of ACC system in traffic conditions[8]

Interesting is the decline in the usage of the "middle" setting: 1.6s, while the other settings are at about the same level throughout the range of traffic conditions. For the average driver, it means that the physical meaning, seconds, of the most preferred gap settings do not relate to the traffic situation, e.g. otherwise, there would be a trend towards either the longer or the shorter setting. Figure 14 shows the gap usage per driver.

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[8] The traffic speeds range from 10 m/s to 40 m/s consistently throughout the plots in this report. However, insufficient data cause distortions in the observations between 10 m/s and 20 m/s.

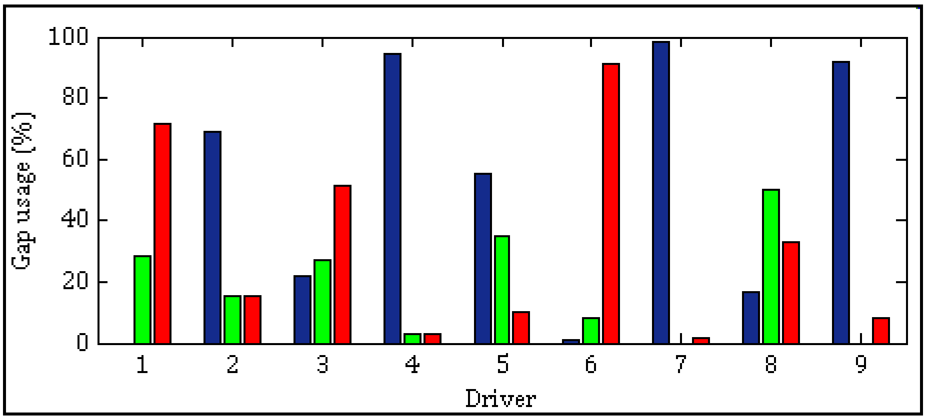

Figure 14: Gap settings of ACC system between drivers

Each driver shows a very distinct pattern in the chosen gap settings. Where drivers 2, 4, 6, 7 and 9 have a clear preference for either the longest or the shortest gap, drivers 1, 3, 5 and 8 chose different levels throughout the test period. For those drivers, traffic could be an argument for changing the gap setting. Figure 15 shows gap setting choices divided between these two groups of drivers. Bars indicate the absolute occurrence of the gap setting, lines the relative occurrence compared to the other groups, in percentages. Black lines indicate the borders of the interval in which the traffic data is aggregated.

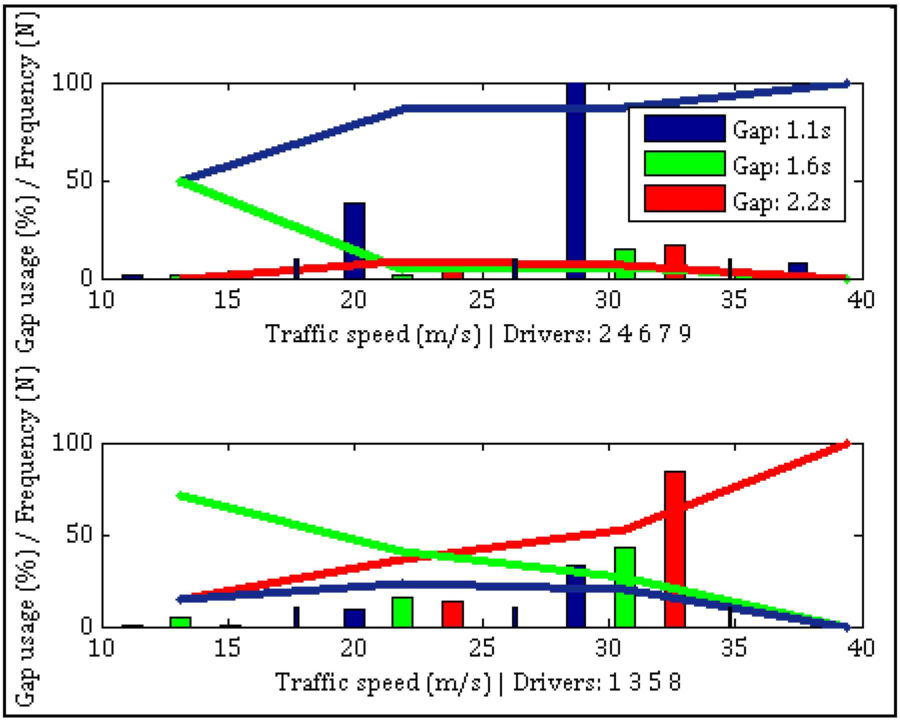

Figure 15: Gap setting of ACC system between groups of drivers.[9]

Group one, consisting of drivers 2, 4, 6, 7 and 9 has a very high overall usage of the lowest gap setting, 1.1s. In addition, this usage falls practically to zero at speeds of around 10 m/s or 15 m/s. The second group declines at about the same rate, but uses different gap settings at different traffic conditions. A high speed, free-flow traffic, sees higher usage of the 2.2-second setting. This group falls back to the 1.1 and the 1.6-second setting when traffic becomes more congested. An explanation could be (i) the level of aggressiveness between different drivers, (ii) the comfortable rate of "experimenting" with the system or (iii) others. While having C/ACC turned off, group 1 and 2 had an average time gap of respectively 1.8 and 2.3 seconds. Gender does not seem to be a good predictor for this difference. Drivers 2,6,7,8 and 9 are male.

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[9] Total frequency of the 1.1-second gap for drivers 2, 4, 6, 7 and 9 at 30 m/s is 222.

Traffic conditions seem not to influence the average chosen gap setting of the drivers. However, a closer look at differences between drivers reveals, at the highest possible hierarchy, a group that is possibly less aggressive and toggles more between the different settings. A statistical test performed on gap behaviour and possible predictor variables such as traffic speed, driver, baseline gap choices sees significant differences between the set gap and drivers and between the set gap and the baseline gap. There are no significant differences between set gap and traffic speed. Appendix 10.9 contains the input, method and output of this test.

4.2.2 Gap settings in CACC

Figure 16 shows CACC gap settings related to the drivers. Equal to the gap setting on ACC, users have a very distinct preference to the different settings. The 0.9-second setting was "on" two times while passing a detector station in a car following mode. All drivers seem to prefer 0.6, 0.7 or the 1.1-second setting.

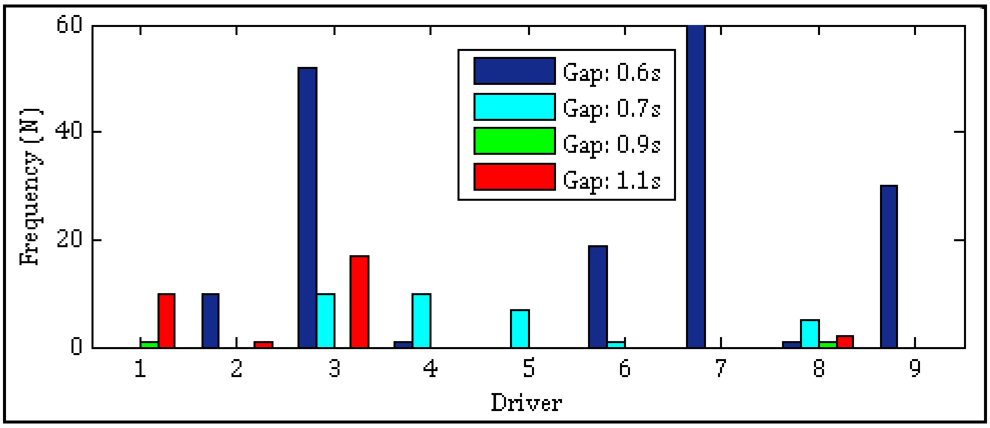

Figure 16: CACC usage among different drivers

Figure 17 presents the chosen gap settings relative to the traffic. A large majority of the passing events had the shortest setting enabled. There is not clear relationship with traffic speed. The fact that the CACC vehicle had to follow the ACC vehicle throughout the trip makes this rather interesting. CACC trips had few individual takeovers or cut-ins compared to ACC. Because of this, the drivers had a greater chance to experiment with the system and to pick their preferences. This cannot be true for 100% of the occasions, CACC usage just as ACC usage is inverse proportional with the traffic speed. Seeing no real change in CACC compared to ACC could imply that drivers stick to their original choice, and just turn it off when that choice does not make driving more comfortable.

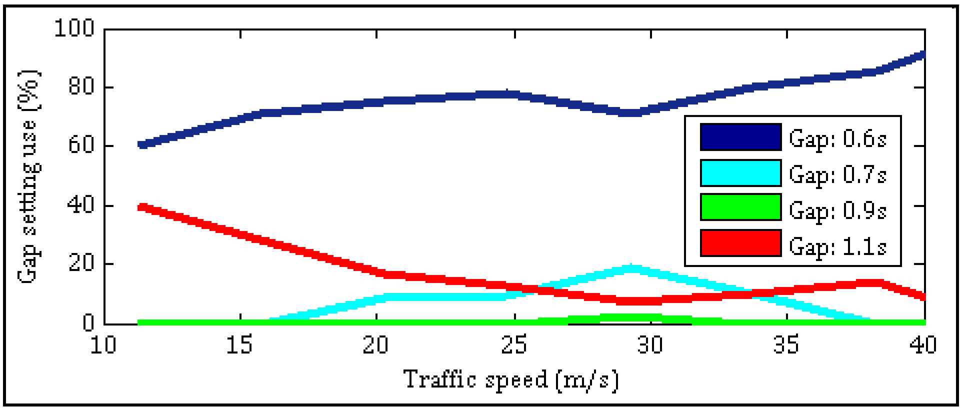

Figure 17: Gap settings with CACC system

4.3 C/ACC usage in traffic condition transitions

Chapter 1 and 2 viewed the drivers' behaviour in static conditions, i.e. the behaviour of drivers at a certain conditions. This chapter will analyse the relationship between C/ACC usage and changes in those conditions. A relevant question: does the rate of traffic change reflect a certain rate of change in C/ACC usage?

A transition matrix containing transitions between traffic speeds shows the impact of those transitions on average C/ACC usage. Appendix 10.10 explains the method for obtaining this information. Table 3 contains a transition matrix. Speeds measurements are rounded to the nearest multiple of 5.[10]

The entry "17 (+14)" (row 2, column 5) in the field has the following meaning: The speed increased from 10 to 25. This resulted in an average of 17% C/ACC usage, which is up from 3% at when the traffic speed was 10.

Table 3: C/ACC usage at t=1 (%) (Change from t=0 (%))[11]

Speed t=0 (m/s)		*Speed t=1 (m/s)*							
		5	10	15	20	25	30	35	40
	5	0 (0)							
	10		0 (-1)	8 (+5)		17 (+14)			
	15			21 (+8)		75 (+75)	65 (+64)	73 (+70)	
	20		0 (-18)	8 (-19)			69 (+62)		
	25		0 (-52)			22 (-7)	60 (+11)	74 (+33)	
	30			9 (-35)		45 (-28)	62 (-1)	78 (+18)	
	35				4 (-67)	68 (-23)	56 (-23)	84 (-1)	
	40							81 (+29)	30 (-17)

Some interesting observations follow from Table 3. Obvious is the increase in C/ACC usage when traffic is speeding up, the right upper triangle, and the decrease in C/ACC usage when speed is slowing down, the left lower triangle. This general observation comes from chapter I of this analysis section. Traffic changing from 15 to 35 had 70% of the times the consequence that C/ACC status is changed from 'off' to 'on', a greater increase than when going from 25 to 35 or from 30 to 35. However, this increase is solely due to the increasing chance that C/ACC is already active in the first place. When this is accounted for, rapid increases in traffic seem to have a lagging effect on C/ACC usage. An increase from 10 to 25 causes C/ACC usage to rise to 17%. An increase from 15 to 25, however, causes C/ACC usage to rise to 75%, from 0% in the first case.

Traffic speed decreasing to 10, whether it started at 25, 20 or 10, has the effect that every driver still using the system deciding to turn it off. A large 'breakpoint' in the turning off cases is visible between traffic speeds of 20 and 25. When drivers are in traffic that decreases the speed from 35, a free-flow speed, to 25, the majority leaves the C/ACC "on". Starting at the same speed and going to 20, in the same time interval, has the effect that almost all drivers who had the system "on" in the first case, turn it "off". Only 4% C/ACC usage remains.

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[10] All speeds in this section report in meters per second (m/s); leaving further annotations out.

[11] Fields containing five or less data points are blank because of questionable accuracy or missing data.

4.4 Drivers' reported behaviour

Apart from the quantitative data as described above, there is qualitative data from the drivers' answers to the questionnaires. Appendix 10.11 contains the answers of which this summary is created. Two sections divide this summary; overall usage related answers and gap setting related answers.

4.4.1 General C/ACC usage

Drivers reported improvements in comfort, convenience and enjoyment for both the ACC and the CACC system. The former being in line with a study done by Hoedemaeker and Brookhuis that concluded, "ACC was assessed favourably with respect to effort, comfort and usefulness" [Hoedemaeker & Brookhuis, 1998]. In addition, participants in general consider CACC to be less safe than ACC or manual driving. Combined with the higher CACC than ACC usage, this implies that the circumstances of the test favoured the use of CACC. Possible reasons are (i) the presence of a PATH employee in the vehicle, (ii) the required following of the ACC vehicle or (iii) others.

In terms of the systems' relation to other traffic, neither ACC nor CACC caused the driver to significantly change the vehicle's speed from that of the rest of the traffic. In addition, drivers reported no change in their own regular speed. Both apply to all traffic conditions. The performance of the system can therefore not be considered causing the observed decline in C/ACC usage along the traffic speed.

The nature of the system, regulating speed based on time gap, did cause a significant change in the level of comfort related to the traffic. Nearly all drivers reported a level of comfort of 7 on a scale from 1 through 7 whilst in "light" traffic. This mark drops to 3 in "heavy" traffic. Drivers prefer manual driving in those conditions above C/ACC controlled driving. From the two aspects C/ACC is controlling, speed and gap, drivers noted that speed was not significantly different between their normal driving and their C/ACC driving.

4.4.2 Gap usage

Related to gap settings, the average driver reported that the level of comfort on both ACC and CACC declined with a shorter gap. However, the standard deviation greatly increased with a shorter gap. This could mean some drivers are comfortable with any gap, while others only choose the longest gap and are not pleased with anything shorter. In addition, the time gap participants used were all longer than usual in congested traffic, for the ACC system, and shorter than usual in light traffic, for the CACC system. This means the preferred gap settings change according to the traffic conditions. Hoedemaeker and Brookhuis hypothesised that an "ACC that adopts a default headway equal or close to preferred headway would be more acceptable to drivers" [Hoedemaeker & Brookhuis, 1998]. This seems to be in line with findings from this questionnaire. Also, only 15% of the C/ACC active periods saw a change in the gap drivers choose, for the first two weeks of driving a new vehicle with a new ITS. This could mean that although drivers prefer a different setting, they are reluctant to change the gap. Instead, they turn the system off when C/ACC does not improve their comfort.

Combining these findings result in a C/ACC system that changes the gap setting automatically with the traffic conditions. That could greatly increase the usage of ACC in more congested situations.

Observations from the combined qualitative and quantitative data present in the basis of the conclusion of this analysis, presented in the next chapter.

5 Conclusion

The accuracy needed for the implementation of traffic data into microscopic vehicle data allows for neither spatial nor temporal aggregation of the detector data. This research therefore conducted the analyses with 30-second interval data from one station at the time. However, there is large variability in both the location and the content of the traffic data. The solution is to aggregate multiple microscopic observations in order to create useful visualisations of the data.

These visualisations show high occupancy or low traffic speed to cause a decline in the use of C/ACC. This decline is relatively linear across speeds ranging from 10 m/s to 40 m/s. Dense traffic results in 10 to 20 % C/ACC usage, light traffic in 80 to 90%. This is in line with other research conducted and may not be very surprising.

Qualitative analysis tells that the reason for abandoning the C/ACC system in high traffic do not lie in the performance of the system; characterising performance in terms of speed. However, the chosen time gaps seem to be too long in dense traffic for the ACC and too short in light traffic for the CACC system. The major qualitative argument for the declining usage is the "comfort" people have with the system. Drivers base their gap settings primarily on their own, rarely fluctuating, preferences. Of the C/ACC active periods, 85% did not have a change in gap. This could mean that, to state it rather boldly: drivers pick what they like when turning the system on, and turn the system off when they are not comfortable with this initial pick. Following this line of argument, a gap that dynamically changes according to traffic conditions should greatly increase the activation rate of both ACC and CACC in congested traffic.

The ability to test both ACC and CACC systems revealed no statistical significant higher usage for CACC. This is odd, given that the level of comfort, enjoyment, convenience and safety is higher with ACC. This means that either: (i) having a PATH employee in the passenger's seat or (ii), being obliged to follow one other vehicle is causing this difference.

In terms of transitions between different traffic states, there are two interesting observations. (i) There is clear lag in the activation of C/ACC in traffic that is speeding up. Going from 10 m/s or 15 m/s to 25 m/s results in respectively a 17% or a 75% increase in C/ACC usage. (ii) The breakpoint in C/ACC usage lies between 20 m/s and 25 m/s. When speed is decreasing from free-flow, 35 m/s, to 20 m/s or 25 m/s the result is a decrease in respectively 67% or 23% percent. Of the participants who have the system "on" in the first case, 80% shut it down between those speeds.

As a concluding statement; there are well-defined conditions in which the drivers activate or deactivate their C/ACC. This is mainly due to comfort and the gap setting performances. Dynamically changing gaps with traffic without the need for any user's intervention will greatly increase the potential of both ACC and CACC.

6 Recommendations for future studies

Several recommendations follow from the conclusions in the previous chapter. This research is performed with data from the first 9 drivers observed for the current project at the PATH program. It is intended to expand that number to 16 to 20 drivers. At the time of writing, 12 drivers finished the test. [31 July 2009] This increase in data improves the reliability and accuracy and increases the number of observations of the C/ACC usage. In addition, more driving time per participant and more independent CACC drives increases the reliability of the reported drivers' behaviour. The latter will also make it possible to narrow down the possible differences between CACC and ACC usage. Full range C/ACC removes the bias that results from unknown driver's behaviour close to minimum working speed of the CACC and ACC system. It enables research in stop-and-go traffic.

As stated in the conclusion, dynamically changing gaps will perhaps increase C/ACC usage. Instead of using traffic conditions as an input for the gap setting, the vehicle's speed provides an easy to obtain surrogate to test the potential benefits. This is relatively easy to develop and therefore recommendable as a future study.

7 Acknowledgements

I would like to thank Steve and Rattaphol for their time and their supervision while performing this research, Christopher and Jessica for my very smooth first day and for all the questions about the current project. Bart provided me the opportunity for going to Berkeley, for which I am very grateful. Alje linked me with Bart and Reinier finally pushed me into exploiting this provided opportunity. Without them, I would not be where I am today, literally.

8 Explaining terms

Not all terms in this document are well defined or broadly used. This section will give definitions of these terms as they are used in this report.

Table 4: Explaining terms

Term	*Description*
ACC	Adaptive Cruise Control (ACC) is an ITS which regulates speed in terms of a combination of the users input of fixed vehicle speed and fixed time gap.
Breakpoint	A break in two distinct patterns of C/ACC usage.
C/ACC	Notions of which applies to the ACC system as well as the CACC system.
CACC	Cooperative Adaptive Cruise Control (CACC) is an ITS which relies on the same principle as ACC, but is able to maintain shorter time gaps due to the direct communication with the ACC of the vehicle in front.
Car following mode	The state in which the speed is regulated by a minimum time gap.
Cut-in	A situation in which a third vehicle places itself in front of the C/ACC vehicle that drives in a car following mode.
Detector loop	An inductive loop placed on the surface of a lane to measure certain traffic parameters.
Detector station	A logical collection of detector loops present at the same location on the highway.
District 4	One of the 12 regions that the California department of transportation uses to divide California for administrative purposes
Full range C/ACC	A C/ACC system functioning in all available vehicle speeds.
ITS	An Intelligent Transportation System (ITS) is a collective term for all efforts to integrate ICT to transportation.
Passing-event	A moment in time on which a vehicle passed a detector station.
Speed regulation mode	The state in which the C/ACC system regulates on maximum vehicle speed.
Time gap	The distance in seconds between the front on the vehicle and the back of the preceding vehicle.
Traffic density	The number of vehicles on a stretch of length on the highway.
Traffic flow	The number of vehicle that passed detector loop on the highway in a certain time.
Traffic occupancy	The percentage of time the detector loop of the highway is occupied
Traffic speed	The average speed of the vehicles that passed a detector loop of the highway in a certain time.

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10 Appendices

The following pages contain appendices 1 through 11.

10.1 The drivers protocol

The list below gives the protocol of the C/ACC test drives per driver. For the analyses, data from 9 drivers is used. At the time of writing [18 July 2009], eleven drivers finished the test. There are several requirements to the participants in order to be accepted in the test:

- Have a valid California driver's license
- Have a clean driving record with no moving violations within in the last 3 years and no DUIs
- Commute daily with 25 or more minutes spent travelling at freeway speeds each way
- Have relatively secure parking at both home and work
- Be between the ages of 25 and 55 years of age

The program gave several instructions to the drivers of which these are the most important ones:

- While driving the CACC vehicle, you are following a PATH researcher in the ACC vehicle who is driving below the speed limit.
- While driving the CACC vehicle, a PATH human factors researcher is in the passenger seat adjacent to you.
- You will be entirely free to choose your own driving behaviour while driving both vehicles except for the following:
- You are to be the only one in the vehicle while driving, except for the experimenter during CACC trips.
- You have to operate the vehicle in accordance with all traffic laws.

The program followed the following timetable of driving days per participant:

- Baseline driving: Days 1 & 8
- ACC driving: Days 2, 3, 4, 5, 6, 7, 9, 10 & 11
- CACC driving: Days 12 & 13

10.2 Measured variables

Table 5 contains a list of several variables recorded by either PeMS or the C/ACC vehicle.

Table 5: Several recorded variables

Group	*Name*	*Description*
Trip	Driver	Driver (N)
	Gender	Male or Female (N)
	Vehicle	Silver or Copper (N)
	Date	Date (YYYYMMDD)
	Trip ID	Unique number for every different trip (N)
	Commute	Practice, morning, evening or urban (N)
	Trip mode	Baseline, ACC or CACC (N)
Drive	Time (vehicle)	Time according to vehicle (HH:MM:SS.FFF)
	Time (UTC)	Time corrected to UTC (HH:MM:SS.FFF)
	Accl. (x)	Longitudinal acceleration (g)
	Accl. (y)	Lateral acceleration (g)
	Brake	Brake (0/1)
	Brake pres.	Pressure (bar)
	Speed	Vehicle speed (m/s)
	Time (GPS)	Time according to GPS (HH:MM:SS)
	Longitude (GPS)	Coordinate (N)
	Latitude (GPS)	Coordinate (N)
	Altitude (GPS)	Altitude of car (m)
	Speed (GPS)	Speed according to GPS (m/s)
	ACC Enabled	ACC system on (0/1)
	ACC Active	ACC system active (0/1)
	Set speed	Speed set by driver (m/s)
	Car space	Gap setting (0 (off) to 7 (2.2 seconds))
	App. Warn.	Approach warning (0/1)
	Buzzer 1	Warning to user 1 (0/1)
	Buzzer 2	Warning to user 2 (0/1)
	Buzzer 3	Warning to user 3 (0/1)
	Target lock	Target lock on lead vehicle (0/1)
	Distance	Distance to lead vehicle (m)
	Time gap	Time gap to lead vehicle (s)
	Relative speed	Relative speed to lead vehicle (m/s)
	Lead vehicle speed	Lead vehicle speed (m/s)
Traffic	Time (detector station)	Traffic data collection time (HH:MM:SS.FFF)
	Traffic flow	Traffic flow (vehicles/ sample period)
	Traffic occupancy	Traffic occupancy (%)
	Traffic speed	Traffic speed (m/s)
Location	Station ID	Unique station identifier (N)
	Absolute post miles	Highway post miles (m)
	State post miles	Highway post miles (m)
	Highway	Highway number (N)
	Direction	Highway direction (N,E,S,W)
	Sample period	Recording time (s)

10.3 Map of driving locations

Figure 18 lists the detector stations for Caltrans district 4.

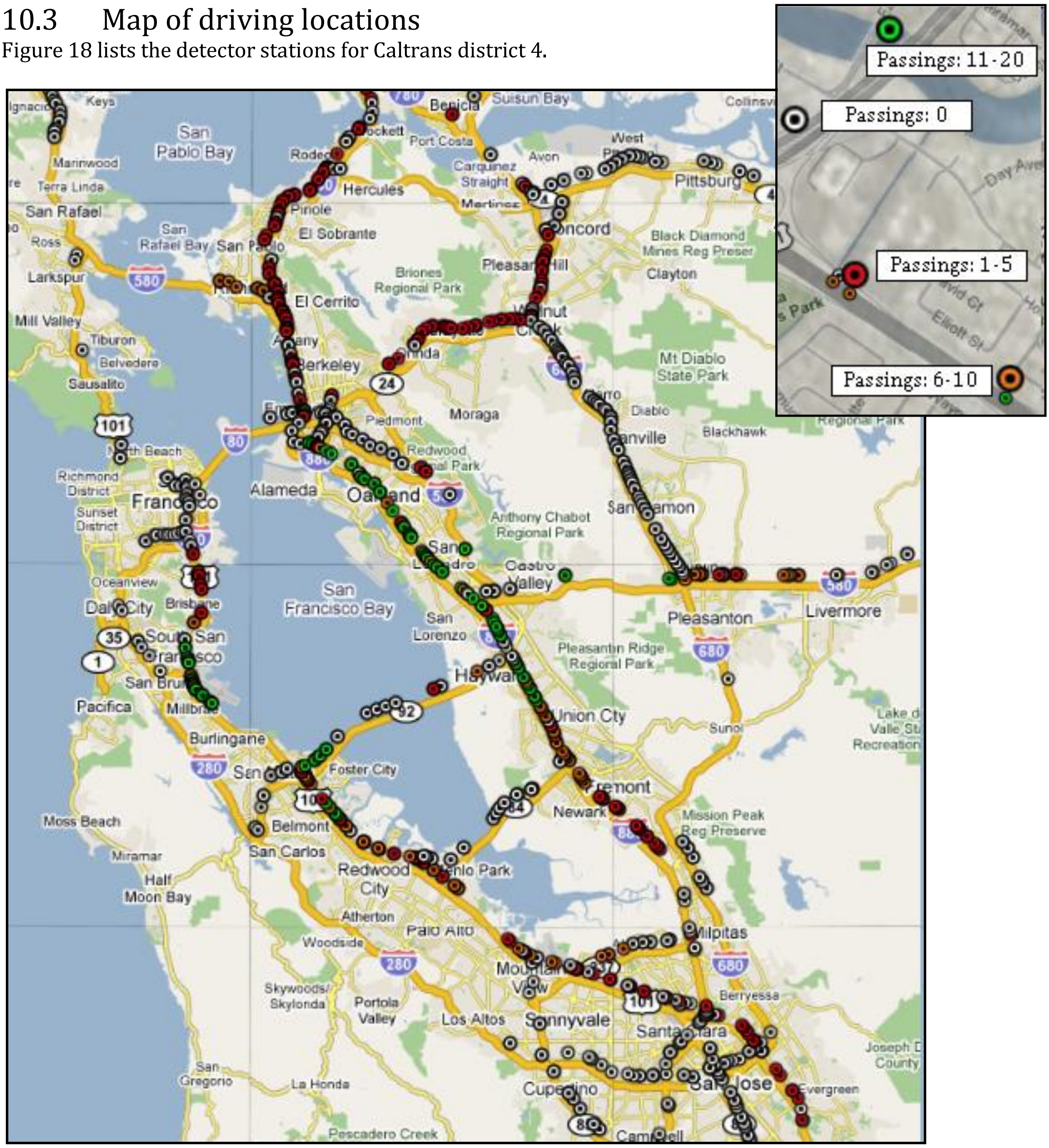


Figure 18: Detector stations in Caltrans district 4.

The dots represent the number of passings of drivers 1 through 9.

10.4 Cleaning data

This appendix gives the reasons and method used for cleaning the data.

Table 6: Data cleaning

Parameter	*Description*
Occupancy greater than 50%	"Typical values for midday traffic are around 5-15%. During an incident the occupancy can spike up to 25-35%." [PeMS, n.d.] This means 50% is clearly out of range.
Speed greater than 50 m/s	Obviously not trustworthy as a measurement for traffic conditions. Keep in mind that this is an average traffic speed.
Flow greater than 3000 vehicles/lane/hour	"The maximum value of flow for a freeway lane is around 2000-2200 vehicles per hour." [PeMS, n.d.] Flows greater than 3000 vehicles/lane/hour are therefore out of range.
Difference between speed and vehicle speed more than 15 m/s	Now the vehicle is in clearly different conditions than the vehicles on surrounding lanes.
Stations not in travel direction	Due to the nature of the algorithm, something stations are included that are in the opposite travel direction. Smart software looks which direction in a highway travel section is clearly dominating other found directions. In addition, if the participant drove both directions in one trip, the trip is separated into two distinct events.
Stations with no traffic data	Unable to analyse, therefore removed.
Vehicle length greater than 12 meters	Note that this is the average vehicle length over 30 seconds and over all lanes. 12 meters, 40 foot, is the maximum allowed length of a single vehicle unit in California. [California Office of Legislative Counsel, n.d.] Although longer vehicles exist, these are not likely to be the average across all lanes for 30 seconds.
Vehicle length smaller than 2.5 meters	Note that this is the average vehicle length over 30 seconds and over all lanes. 2.5 meters is the length of the smallest available SMART vehicle. [SMART USA, n.d.]

Vehicle length calculation: the formula below gives the average length of the vehicles over all lanes for a specific period in time.

$$\boxed{Length_{average} = \frac{\left(\frac{1}{n}\sum_{1}^{n} Occupancy_n\right)[\%] \cdot \left(\sum_{1}^{n} \frac{1}{Flow_n} Speed_n\right)[m/s]}{\left(\frac{1}{n}\sum_{1}^{n} Flow_n\right)[veh/s]}}$$

Figure 19: Vehicle length calculation

10.5 A passing event with temporal data intervals

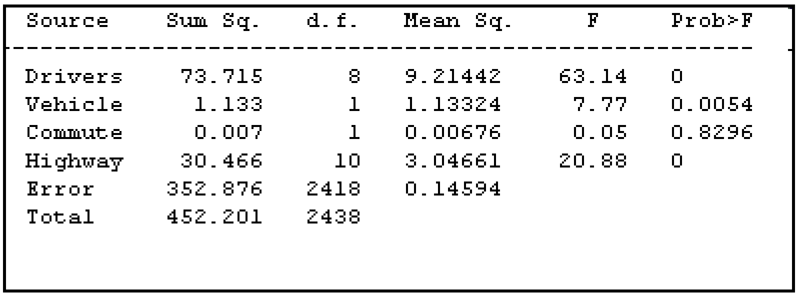
This appendix contains an example of a temporal data interval as it is included in the dataset that describes C/ACC usage.

Table 7: Passing event

Time	*Event*
11:14:38	Start of the interval that describes drivers' behaviour related to the traffic.
11:15:00	Start of the traffic measurement interval.
11:15:08	Vehicle passes the detector station.
11:15:30	End of the traffic measurement interval.
11:15:38	End of the interval that describes drivers' behaviour related to the traffic.

10.6 Analysis of variance on drivers and system

An ANOVAN, n-way analysis of variance, can test if the differences observed in the C/ACC usage of the drivers and the system, ACC or CACC, is statistically significant. The trips of drivers 1 through 9 served as input for this test. The variables are tested for different averages, e.g. if the averages of drivers 1 and 2 are different and if that is so, how that difference relates to the different C/ACC usages within a driver itself. The F value of Figure 20 shows the ratio between those two differences.



```
Source      Sum Sq.     d.f.     Mean Sq.       F      Prob>F
-----------------------------------------------------------------
Drivers      73.715        8     9.21442      63.14    0
Vehicle       1.133        1     1.13324       7.77    0.0054
Commute       0.007        1     0.00676       0.05    0.8296
Highway      30.466       10     3.04661      20.88    0
Error       352.876     2418     0.14594
Total       452.201     2438
```

Figure 20: The output of the ANOVAN-test, as available in MATLAB ®.

Noticeable are the significant differences in C/ACC usage between the drivers, vehicle and highway. The last can be explained by the fact that every driver had distinct commutes with therefore distinct highways. Commutes are divided by "mornings" and "evenings". There is no significant difference in the C/ACC usage between those two types of commutes.

10.7 Usage of C/ACC over length of experiment

Figure 21 shows a graph of C/ACC usage over the length of the experiment, omitting baseline drives.

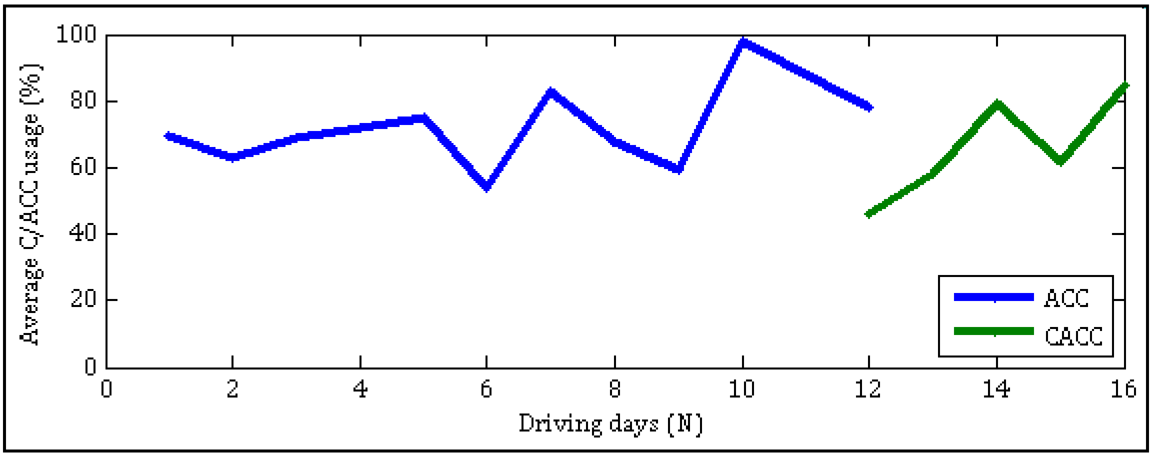


Figure 21: Average C/ACC along experiment

10.8 Coding driving states

Several events are not measured by the computers in the vehicle, but can be important for the improvement of several analyses. Behaviour of drivers can depend, for example, on whether the vehicle was in a "car-following" or a "speed regulation" situation. This situation can be identified by the difference between the set time gap and actual time gap. For instance, if the set time gap is 2.2 seconds but the vehicle in front is driving 3 seconds ahead, the C/ACC system will regulated based on the maximum given speed. However, if the time to the preceding vehicle is close to 2.2 seconds, but the vehicle speed is already at the given maximum, or set speed, there is also no case for "car following". Figure 22 shows these two measurements for "mode identification".

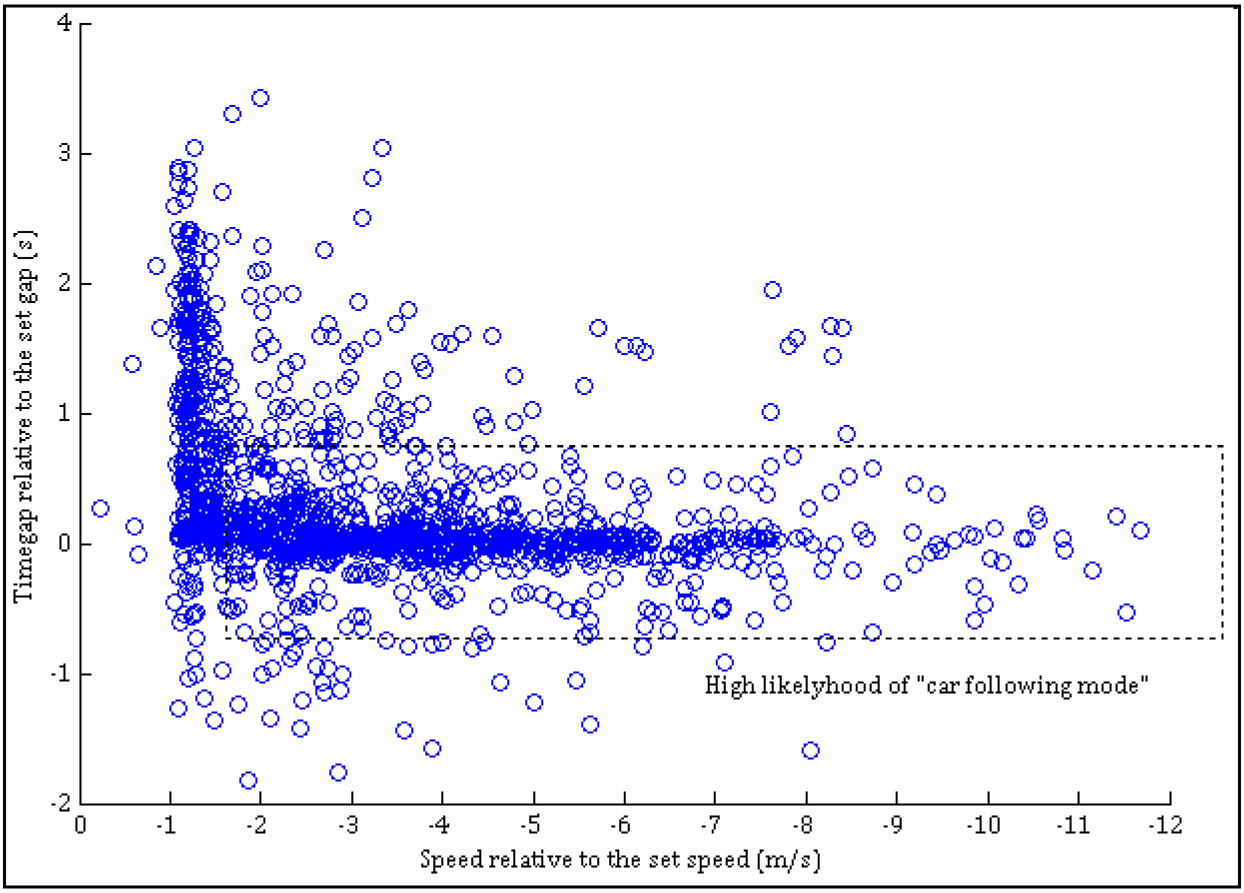


Figure 22: Graph on which mode identification is based.

Interesting is that the set speed measurement differs from the vehicle speed measurement by around 1 m/s. Based on this figure, the "subjective" decision is to classify all events within the rectangle as "car following mode".

10.9 Analysis of variance on gap setting and traffic

Three one-way ANOVA tests are performed on the gap setting choices while the results are shown through boxplots. The red line is the median, the blue area is where the data between the first and the second quartile lie, the black line presents the 95% confidence interval. The red crosses are outliers.

The first is an ANOVA on the different gap settings and the different drivers. The result is statistically significant.

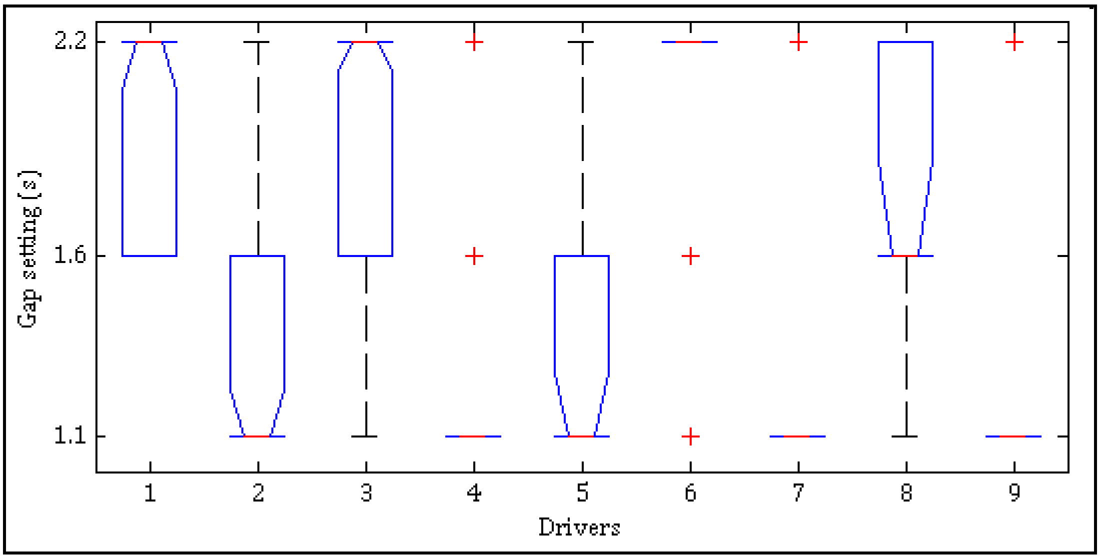


Figure 23: Gap settings by different drivers

The second ANOVA is performed on traffic speed and gap setting. The difference was statistical significant. The boxplot shows there is no relationship between the physical interpretation of gap setting, seconds, and traffic speed.

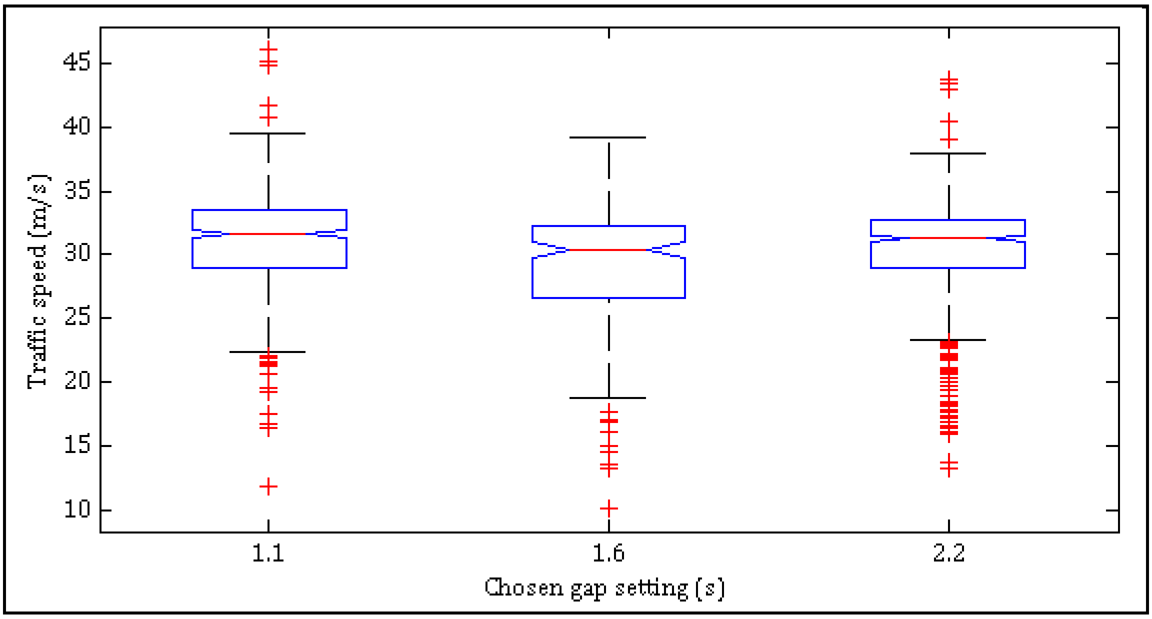


Figure 24: Boxplot for the ANOVA on gap and traffic speed.

The third ANOVA is on the average set gap per driver and the gaps that driver used in the baseline drives. The boxplot shows on the x-axis the drivers. The black dots show what the average gap is while driving ACC. The boxplot presents the variation in time gaps for the baseline trips. The result is statistically significant.

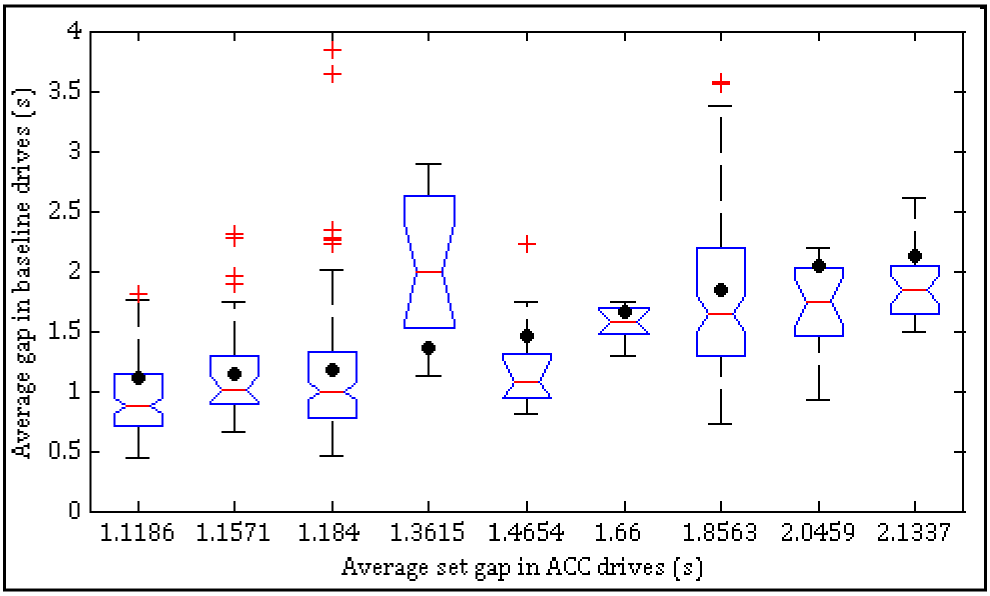


Figure 25: Set gap related to actual gap in baseline drives.

Interesting is the visible trend. The drivers, who normally drive with gaps under 1 second, choose overwhelmingly for the 1.1-second gap, the smallest available, while driving ACC. In addition, baseline gaps range more than there appropriate gap choices.

10.10 Creating a transition matrix

A transition matrix shows the changes of a certain parameter in the transition from one condition or state into another. In this case, traffic speed is used as the condition and C/ACC usage as the parameter. All cases in which there is detector data available within 2 minutes between subsequent passing events are included. Because traffic is a very dynamic process, intervals longer than 2 minutes could possibly not have the desired causal relationship, e.g. it would probably contain many indirect changes such as traffic speed going from 20 to 30 m/s via 40 m/s.

The change in average C/ACC status between the first 60-second interval and the next 60-second interval are also calculated. This way, change in average C/ACC is measured as a function of traffic speed change. Table 8 states an example of the data for cases in which traffic speed changed from 20 to 25 m/s. The data from Table 8 would result in a data entry of "83 (33)".

Table 8: Example of C/ACC changes

Traffic condition (t=0)	*Traffic condition (t=1)*	*C/ACC usage (t=0)*	*C/ACC usage (t=1)*	*Change in C/ACC*
20 m/s	25 m/s	50%	100%	50%
20 m/s	25 m/s	100%	50%	-50%
20 m/s	25 m/s	0%	100%	100%
Average		50%	83%	33%

10.11 Questionnaire

This table contains the answers of the questionnaire that were used for the qualitative C/ACC usage analysis.

Table 9: Questionnaire answers

Questions	*Conditions*	*Method*	*ACC*	*CACC*
Compare safety (manual driving, ACC, CC, CACC)		Rank	1 to 3 (least safe)	1 to 4 (least safe)
		Mean (std)	MD 1.33 (.51)	ACC 1.2 (.44)
			ACC 1.67 (.51)	MD 2 (.70)
			CC 2.83 (.4)	CACC 2.6 (1.14)
			-	CC 3.4 (.894)
While driving C/ACC, were you driving slower or faster than you normally drive?		Rating	1 to 7 (faster)	1 to 7 (faster)
	Heavy traffic	Mean (std)	3 (1.09)	3.6 (1.94)
	Moderate traffic		3.83 (1.32)	4 (1.22)
	Light traffic		4 (1.4)	4 (1.22)
When using C/ACC, did you follow other vehicles closer or further than you normally do?		Rating	1 to 7 (Further)	1 to 7 (Further)
	Heavy traffic	Mean (std)	4.5 (1.04)	4 (1.58)
	Moderate traffic		4 (1.09)	3.4 (1.51)
	Light traffic		3.83 (1.16)	2.8 (unknown)
How comfortable were you using the ACC system in the following traffic conditions?		Rating	1 to 7 (Very)	1 to 7 (Very)
	Heavy traffic	Mean (std)	3.17 (1.94)	3.2 (2.28)
	Moderate traffic		5.67 (1.36)	5.4 (1.67)
	Light traffic		6.83 (.4)	5.8 (1.78)
When driving C/ACC, was your speed generally slower or faster than the speeds of neighboring vehicles?		Rating	1 to 7 (Faster)	1 to 7 (Faster)
	Heavy traffic	Mean (std)	3.33 (1.03)	4 (1.41)
	Medium traffic		3.83 (1.169)	4.4 (.54)
	Light traffic		4.33 (1.5)	4.4 (1.5)