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Development and Evaluation of Selected Mobility Applications for VII

Steven E. Shladover, et al.

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PATH Research Report on Task Order 6224

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Abstract

This report describes the development of two of the three mobility applications that PATH is developing and evaluating under the sponsorship of the FHWA Exploratory Advanced Research Program, with cost share funding provided by PATH TO 6224. These applications are intended to use DSRC wireless communications among vehicles and between vehicles and the roadway infrastructure to improve mobility on limited-access highways. The first application combines ramp metering with variable speed limits to enhance control of traffic so that traffic flow breakdowns can be deferred or avoided at bottleneck locations. The second application uses vehicle-vehicle communication to improve the performance of adaptive cruise control systems so that they can operate safely with smaller longitudinal gaps and vehicle-roadside communication to provide adjustments to their set speed and gap settings to adapt to changes in local traffic conditions.

Key Words: active traffic management, variable speed limits, adaptive cruise control, cooperative adaptive cruise control, DSRC applications

Executive Summary

This report describes the development of two of the three mobility applications that PATH is developing and evaluating under the sponsorship of the FHWA Exploratory Advanced Research Program, with cost share funding provided by PATH TO 6224. These applications are intended to use DSRC wireless communications among vehicles and between vehicles and the roadway infrastructure to improve mobility on limited-access highways. The first application combines ramp metering with variable speed limits to enhance control of traffic so that traffic flow breakdowns can be deferred or avoided at bottleneck locations. The second application uses vehicle-vehicle communication to improve the performance of adaptive cruise control systems so that they can operate safely with smaller longitudinal gaps and vehicle-roadside communication to provide adjustments to their set speed and gap settings to adapt to changes in local traffic conditions.

Variable Speed Limits

The selection of variable speed limits to reduce traffic breakdowns is based on careful modeling of the traffic dynamics and estimation of the probability of breakdown as a function of traffic speed and density. A second-order macroscopic traffic flow model, representing an enhancement of the METANET model, is described and calibrated using detailed traffic data from the Berkeley Highway Laboratory (BHL). The probability of breakdown is estimated for each segment of the BHL test section based on a full week of empirical data, and these breakdown probabilities are then used as constraints on the selection of preferred reference speed and density.

In order to avoid the complexity of simultaneous optimization to select the preferred reference speed and density, it has been assumed that the ramp metering strategy will be defined first, and that strategy will govern the density in each highway segment. Then, the preferred reference speed for each section is chosen using a model predictive control strategy, based on sequential quadratic programming optimization. An example application of the method to the BHL test section is shown to produce a significant reduction of travel delays based on the macroscopic model. In parallel, a microscopic simulation of the same corridor is being developed to provide a more accurate means of testing strategies and predicting their impacts on traffic. The development of this simulation is described.

Cooperative Adaptive Cruise Control

The human factors experiment involving naïve drivers from the general public driving the production adaptive cruise control system and the new cooperative adaptive cruise control (CACC) system is described. The initial results, from the first 12 of 16 test drivers, are reported here. These include survey results, quantitative measurements of driving performance, and comparisons of driving performance with local traffic conditions recorded in the PeMS database.

The initial results show that the drivers have a very favorable reaction to both types of adaptive cruise control. They are more likely to use the systems when traffic is flowing well than when traffic gets heavily congested, since the systems are not designed to cope with stop-and-go

conditions. Each driver tends to converge on a selection of ACC time gap setting that he or she prefers, and does not adjust that setting based on traffic conditions. Rather, when traffic gets too dense they tend to deactivate the systems rather than modifying the gap setting to adapt to traffic. Most importantly, even though the selection of gaps for the production ACC system was relatively well balanced between the longest and shortest settings, when the drivers were given the higher performance CACC system they tended to gravitate strongly towards the shortest settings. This has favorable implications for use of CACC to improve highway capacity and traffic flow.

Applicability of Results to Transportation Problems

This Task Order corresponds to the first half of the matching federally sponsored project, and it will be followed by a new project to match the second half of the federal project, producing the definitive final results. Consequently, the results reported here are interim steps toward those results. Nevertheless, based on these initial results it appears that variable speed limits have significant promise as a strategy to help delay or avoid traffic breakdowns, and they should be seriously considered for a full-scale field test to demonstrate how they would work in practice. Based on the preliminary results from the CACC testing, it appears that drivers are very comfortable with the shorter gap settings provided by this system, which means that widespread use of CACC offers the possibility of significantly increasing the capacity of a highway lane and reducing shock wave disturbances in traffic.

These initial findings should be confirmed by the work that is continuing in the next stage of the federal project and the follow-on state funded project. We expect those results to provide quantitative indications of the extent to which variable speed limits can reduce traffic breakdowns at bottleneck locations and the extent to which use of CACC can increase highway capacity, as a function of market penetration of equipped vehicles.

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Chapter 1. Introduction

1.1 Vision

The performance of our roadway transportation system has long been limited by the low level of integration between vehicles and the roadway infrastructure, which have traditionally operated almost independently (except for the tire/pavement contact patch). The wireless DSRC data communication system being developed under the Vehicle-Infrastructure Integration (VII) initiative (rebranded as IntelliDrive after the project was initiated) offers an extraordinary opportunity to connect the vehicles and roadway infrastructure (and vehicles with each other) so that they can operate as a truly integrated transportation system. Although such integration has been implemented for a long time in the rail and air transport modes (and to some extent in the marine mode as well), it has been elusive until now in the much larger road transportation system.

The VII initiative focused on development of the wireless communication link and its directly related technologies (vehicle positioning and infrastructure-based data handling). Some of the earliest expected applications of the VII technology (called Day One use cases) are also being defined and explored, but there has been little if any attention to the longer-term applications, which have the potential to produce significantly larger improvements in transportation system performance. This project aims to make a large step toward defining several of these key applications and showing their potential contributions to improving mobility by smoothing out disturbances in highway traffic and increasing the capacity per highway lane so that congestion can be mitigated.

The limitations in today's highway capacity and most of the disturbances to the stability of traffic flow are direct consequences of the performance limitations of drivers, combined with limitations in the information available to inform their driving decision making. Drivers are not able to judge their distance or closing rate relative to other vehicles or their position within a lane with the accuracy that modern sensor systems can. Sensors that can measure these variables accurately are still limited by line of sight considerations, and cannot detect traffic conditions with high fidelity at long range. More complete information about both local and regional traffic conditions can only be provided by active communication of data to vehicles.

In addition to their perceptual limitations, drivers also have significant variations in their response times for acceleration, deceleration and turning maneuvers. This limits their ability to control vehicle speed and steering, and requires them to maintain substantial separations relative to other vehicles in order to feel secure and comfortable. Modern highway lanes are twice the width of large passenger cars, and the mean longitudinal separation between vehicles driving at maximum lane capacity (2200 vehicles/hour) at highway speed (60 mph) is about nine car lengths. The combination of these two factors means that the vehicles are only occupying about 4.5% of the roadway infrastructure surface area when the roadway is operating at its maximum throughput (or efficiency). If this percentage can be increased even moderately by use of communication and control technology, the roadway efficiency improvement would be very large.

The drivers' limitations can be overcome through the combination of information and control technology, building on VII technology to:

(a) provide real-time traffic condition information of unprecedented accuracy and completeness, with each vehicle serving as a traffic data probe;
(b) provide customized target speed guidance to vehicles, so that they (or their drivers) can be advised to travel at a speed that will be favorable not only for its own driver but for the flow of all traffic sharing its highway;
(c) enable vehicles to receive detailed real-time driving status information from neighboring vehicles, so that their driving can be closely coordinated to reduce the needed separation and the propagation of disturbances.

The control technology uses the enhanced data to command vehicle movements reliably and accurately, so that shock waves can be minimized and vehicles can drive closer together without sacrificing speed or safety. This means that traffic flow can be smoother and each unit of roadway infrastructure can accommodate a higher traffic volume, improving mobility in two ways.

This project is expected to contribute to future mobility improvements by facilitating the implementation of:

(1) Innovative traffic management strategies that provide real-time speed recommendations to vehicles so that highway traffic flow disturbances can be minimized and attenuated more rapidly and thoroughly than today;
(2) Traffic-responsive cooperative adaptive cruise control systems that can increase the throughput capacity per lane while providing drivers with smooth, comfortable and reassuring driving performance;
(3) Automated driving of heavy trucks on truck-only lanes, significantly increasing the throughput capacity per lane while reducing the aerodynamic drag and fuel consumption of the trucks. Note that this third application, while a part of the FHWA project, is not addressed further in this report because it was not funded under TO 6224.

1.2 Mobility-Enhancing Services

The first mobility-enhancing service is the use of speed advisories to improve highway traffic flow. Until now, the available method for regulating highway traffic flow has been ramp metering, which controls traffic volume or average density, but not speed. The VII communication capabilities will make it possible to sample real-time vehicle speed data with unprecedented scope and accuracy and to communicate the recommended speed to each equipped vehicle, which was not previously possible, without the need for expensive gantries and variable message signs. This, in combination with cruise control systems (including adaptive cruise control), gives the highway operator an unprecedented opportunity to directly control the speed as well as volume of highway traffic, so that the effects of traffic disturbances can be minimized and flow can be stabilized to maximize the level of service to highway users.

The second mobility-enhancing service is cooperative traffic-adaptive cruise control, extending beyond the traffic smoothing potential of the speed advisories to enabling significant increases in lane capacity. Prior research by the project team has already shown the potential for operating adaptive cruise control (ACC) at smaller time gaps than the current generation of autonomous (sensor-based) ACC by using the vehicle-vehicle communication capabilities of VII to coordinate vehicle responses. The new element added here is the addition of information communicated from a wider range of vehicles, so that the cooperative ACC can adjust its set speed and following distance based on downstream and adjacent-lane traffic conditions outside the range of the ACC sensor system. This type of information can only be provided by a VII-like communication capability. It offers the opportunity to achieve lane capacity close to twice as high as today's capacity (if all vehicles were to use CACC at the minimum time gap), while also smoothing traffic disturbances and making the ACC performance appear more natural and sensible to the driver, increasing driver acceptance.

1.3 Overview of the Rest of This Report

This report describes the work that has been accomplished on the state-funded tasks of the Exploratory Advanced Research Project during the period of performance of TO 6224 (July 2008 through September 2009).

Chapter 2 gives the overview of the technical approach that has been adopted in the active traffic management area. Chapters 3 and 4 respectively describe the macroscopic and microscopic modeling approaches that have been adopted, and Chapter 5 describes the technical approach using mathematical optimization to choose the preferred speed limits and ramp metering rates. Chapter 6 describes the estimation of traffic breakdown probability, which is used to define constraints in the optimization process.

The technical background on development of the cooperative ACC system and the design of the CACC experiment and data acquisition system were already documented in the final report on TO 6202, which is UCB-ITS-PRR-2009-23. The method of analysis of the data recorded on the instrumented ACC vehicles is described in Chapter 7, and the results of this analysis are presented in Chapter 8. The effects of local traffic conditions, determined using the PeMS freeway traffic database, on ACC usage are explained in Chapter 9. Chapter 10 explains the next steps, including the integration of the active traffic management and CACC elements to provide traffic-responsive CACC.

Chapter 2. Technical Approach for Active Traffic Management

The concept of Active Traffic Management has been receiving increasing attention in recent years, with significantly more progress toward implementation in Europe than in the U.S. The term has almost become too popular for its own good, and has been used to embrace a wide variety of traffic management techniques. In this project, it specifically refers to variable speed limits combined with cooperative ramp metering, enabling coordinated control of traffic flow and speed.

Ramp metering is a well-established strategy for controlling the average density of traffic in a highway section, but there is no currently available strategy for controlling traffic speed. In this project, we combine dynamic ramp metering with speed advisories to provide coupled control of both density and speed (based on enhancements of existing models) and coordinated along a freeway corridor.

Variable Speed Limits (VSL) have been tested in Europe to smooth or homogenize the traffic flow along a stretch of highway. A speed limit was enforced when volume approached capacity, and kept constant along a section of the freeway. Several empirical studies have been conducted in the U.S. since the 1960's for different purposes (to improve traffic safety or work-zone safety, or traffic flow) (Warren, 2003). Recent research by Bertini et.al. (2006) used an empirical approach to investigate the effectiveness of providing feedback to the driver with advisory Variable Message Signs (VMS) in reducing congestion at a recurrent bottleneck. The suggested speed was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver response to the speed limit and messages on the VMS was reasonable, speed was regulated to some extent, and the improvement in safety was more significant than the improvement in traffic flow, up to 20%~30%. Other work showed that speed control was effective to some extent in reducing speed and speed variations, as well as the number of shockwaves. Moreover, it was particularly effective on the portions of freeway where vehicles maintained small driving headways.

The technical approach in this project is based on our experience and understanding of freeway corridor traffic characteristics through the development of the Performance Measurement System (PeMS) (Choe, et.al., 2002) in California, and in traffic modeling, analysis, simulation and optimal ramp metering algorithm development (Horowitz et.al., 2006 and Lu and Skabardonis, 2007). The following two on-going projects have provided much of the technical foundation for the new research:

(a) TOPL (Tools for Operations Planning): The TOPL project is developing tools to (i) specify the actions for planned operational improvements; (ii) quickly estimate the benefits that such actions can realize; and (iii) prepare detection plans to support implementation of actions, accurately measure the ex-post benefits of those actions, and compare them with their ex-ante estimates. It will have facilities to model event scenarios such as lane closures. Application of TOPL can be easily extended to real-time traffic control since PeMS data can be obtained in near real time at 30 s update intervals.

(b) Coordinated Ramp Metering (CRM): A near-global coordinated freeway corridor on-ramp metering optimization strategy and Linear Programming numerical algorithm are already available, with on-ramp queue and off-ramp flow constraints taken into consideration (Gomes and Horowitz, 2006). The current CRM project is designing and evaluating freeway ramp metering control algorithms for a test area in Los Angeles and developing and validating freeway corridor traffic models and observers.

Based on the understanding and tools developed in these projects, the current project is dynamically detecting bottlenecks and determining the real-time effective capacity of each highway section. Mathematical optimization is used to select 'Preferred Reference Speed Limit' (PRS), 'Preferred Reference Density' (PRD), and a section-wise ramp metering strategy to maximize effective throughput and minimize the severity of disturbances. Specifically, the project is (a) developing algorithms to determine corridor-wise PRS and PRD based on the macroscopic models from TOPL with uncertainties accounted for and compatibility with microscopic models taken into consideration; (b) using PRS as the reference speed feedback to the driver (and to the CACC) to improve traffic flow; and (c) using PRD as the reference density for coordinated corridor ramp metering.

The logical flow of information for the two traffic-management related functions (speed advisories and CACC) is shown schematically in Figure 2.1. These functions are being implemented in prototype form for the research project, which is somewhat different from their expected implementation when a mature VII system is deployed. The shaded blocks on the right side of Figure 2.1 represent functions associated with the evaluation of effectiveness in the research project, but would not be part of an eventual deployed system. The stages in the logical flow of system operation are:

1. Collection of data about real-time traffic conditions. Under current conditions, and for purposes of the experiments to be conducted in this project, this will be done using the existing inductive loops installed in the Berkeley Highway Laboratory (BHL) section of I-80 and the BHL video cameras adjacent to I-80. The inductive loop data are archived in the Performance Measurement System (PeMS) database, and the video data are recorded separately. The video data in particular will be used to trace the trajectories of the equipped test vehicles, which will have distinctive marking patterns on their roofs, to show how the adjacent vehicles interact with them when they are traveling at a recommended speed that is slower than the prevailing speeds of their neighbors. In the future real-world deployment, the data collection could be done using probe vehicles equipped with VII wireless capabilities.

2. Data cleansing. The raw data from all the existing sources are fused, filtered and smoothed. Outlying data points need to be removed and missing data points may need to be imputed based on the available data, so that a comprehensive body of data is available for estimating traffic conditions. Data from multiple sources are fused for more accurate and reliable traffic parameter estimation. For the experimental implementation during the project research, the data sources are the inductive loops and video cameras of the BHL on I-80, while for eventual deployment they are expected to be the existing inductive loops and the VII vehicles acting as traffic probes, potentially augmented in some locations by roadside radar or video systems.

3. Traffic parameter estimation. Based on the smoothed and filtered data, the aggregate characteristics of the traffic are estimated as functions of location and time: traffic speed, density and flow rate. The VII probe vehicles can provide speed information essentially continuously in time and space, representing an improvement over conventional infrastructure-based point detectors.

4. Real-time congestion onset detection. For the experimental implementation, this is done using the BHL loop detectors and video systems. With VII probe vehicles eventually providing traffic data continuously in space and time, both the time and location of congestion onset will be readily detectable everywhere.

5. Predicting uncertainties in driver responses. The driving population is highly diverse and different drivers respond differently to speed limits, especially if those limits are significantly lower than the speeds at which they are accustomed to drive. One of the experiments with naïve drivers in the next stage of this project will compare the displayed advisory speeds with the speeds the drivers actually choose to drive, to develop an initial calibration. Future research may include use of roadside variable message signs to display speed limits to all drivers on an instrumented highway section, where their actual responses (driving speeds) can be measured to provide more extensive calibration. Based on the observed distribution of driver compliance with advisory speeds, the appropriate advisory speed can be chosen to produce the desired range of actual traffic speeds (in effect, providing the correction factor for driver non-compliance)

6. Macroscopic traffic simulation. An extended Cell Transmission Model (CTM) of traffic conditions is used to predict the future evolution of traffic conditions in space and time, based on the measured data, estimated traffic parameters, and identifications of congestion onset. The CTM implemented in the original TOPL simulations (both Aurora and CTMSim (http://path.berkeley.edu/topl/)) was for ramp metering only, which means that only first order density dynamics were represented. This has been extended to second order, including speed dynamics, in this project. Since PeMS data can be updated in real time every 30 s and the BHL data can be accessed in real time, those data can be fed into the extended real-time TOPL model for simulation and traffic control purposes. The time horizon used for traffic prediction depends on the algorithm used for traffic control design.

7. Real-time capacity estimation and uncertainty prediction. Most ramp meter control strategies are based on the capacity of the highway section: the flow rate after traffic enters from the on-ramp should be slightly lower than the capacity for sustainable flow. The physical capacity of a highway section is mainly determined by factors such as road geometry, number of lanes available, weather and illumination. Road geometry is a constant factor and weather and illumination generally change slowly and can be estimated/predicted accurately. Loss of lane availability due to incidents and increases in traffic volume need to be detected automatically, generally through indirect measurements of vehicle speed or density changes. The nominal capacity of recurrent bottlenecks, including their dependence on time of day, can be determined based on analysis of archived historical traffic data. Non-recurrent bottlenecks are more challenging, requiring continuous online estimation of traffic conditions as a

function of location and time, which can be summarized in forms such as the Fundamental Diagram (FD). During this research project, this has been based on the measurements by the loop detectors, which are of course only available at specific locations. In the longer-term VII probe vehicle deployment, vehicle speed data will be available continuously across space and time, enabling faster and finer-resolution capacity estimates.

8. Selection of Preferred Reference Speed (PRS) and Density (PRD). The CTM simulations are repeated for a variety of assumed traffic speed and density conditions, so that the resulting traffic conditions can be assessed. Based on comparisons of these results, the preferred combination of reference speed and density for the section of highway is selected. The selection criteria are being determined in the current research, based on standard traffic performance measures such as total travel time, mean speed, and the variability in speed and vehicle spacing across space and time.

9. Selection of ramp metering rate. Based on the selected PRD for the highway section, the preferred ramp metering rates are determined for the ramp meters serving this section.

10. Application of preferred reference speed. The selected PRS is provided as the set speed to the CACC vehicles and as advisory speed to the other vehicles on the highway section.

Because the CACC vehicles have automatic speed control systems, the set speed quickly becomes the actual speed of these vehicles. While they are driving at the set speed, the drivers of the surrounding vehicles will have no knowledge of this set speed and will be driving at their respective preferred speeds and following distances during the upcoming experiment. The interactions between the equipped vehicles and the surrounding vehicles will be observed by the BHL video tracking system, which will make it possible to analyze these interactions afterwards to see how effectively the equipped vehicles could influence the speeds of their neighbors, and whether their slower travel led to excessive lane changing by vehicles behind them whose drivers wanted to go faster.

The recommended speed advisory will be displayed to the drivers of the test vehicles in another upcoming experiment when they are not operating under ACC speed control. In this case, the willingness of the drivers to follow the advisory speed will be observed, particularly as a function of the amount by which it differs from the prevailing speed of traffic surrounding them. When they do modify their speed in response to the advisories, their interactions with the surrounding vehicles will also be observed by the BHL video tracking system, as in the CACC case.

In the future VII-based implementation, much larger numbers of vehicles would be able to receive the CACC set speeds or advisory speeds, but it is not possible to test the effects that this would have using only the two available test vehicles. Those effects will be estimated using traffic simulations, where the interactions between equipped and unequipped vehicles will be represented based on the BHL observations of these interactions with the test vehicles.

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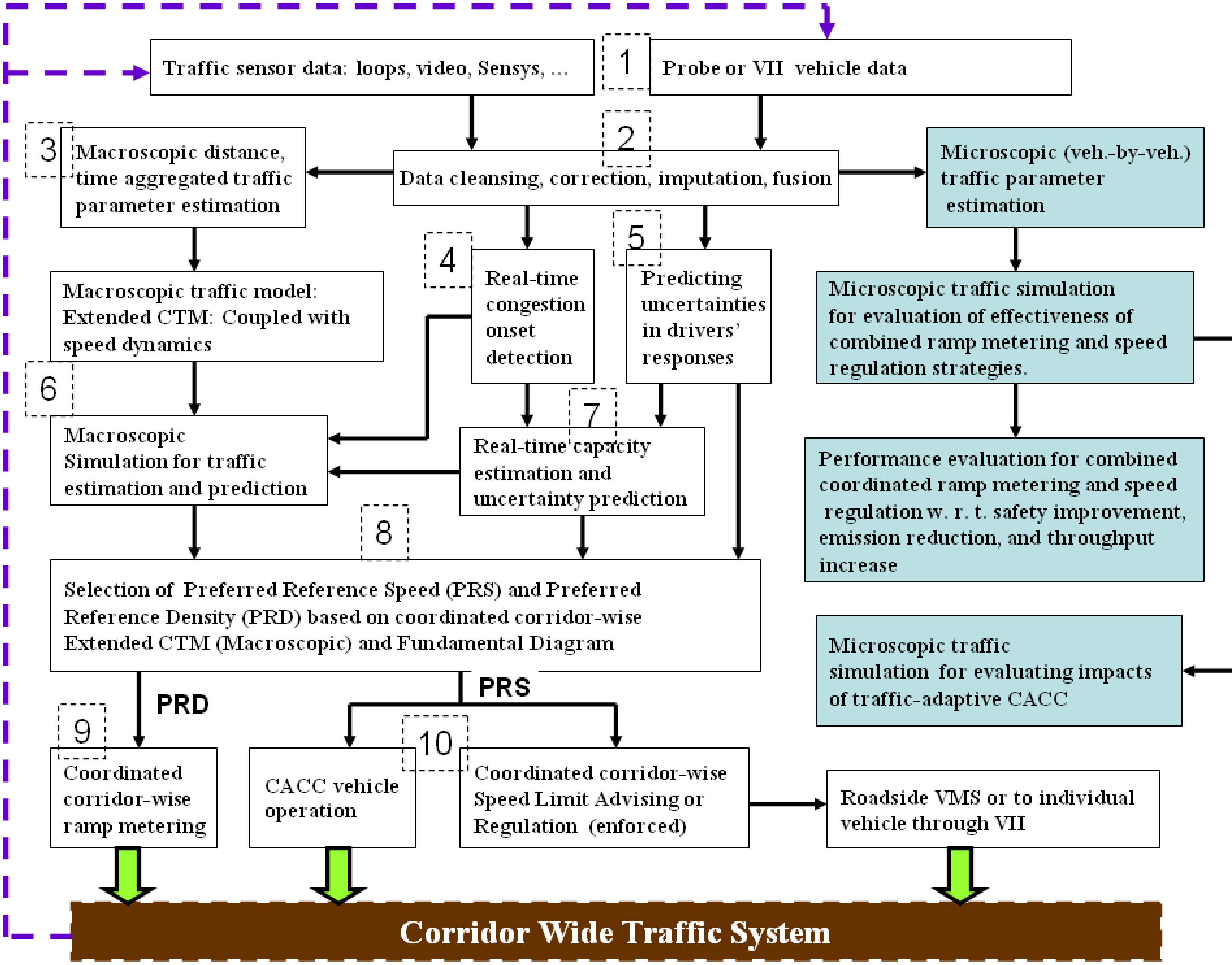


Figure 2.1: Logical Flow of Information for Active Traffic Management Function

Chapter 3. Macroscopic Modeling of Highway Traffic

3.1 Introduction

In recent years, model-based traffic control design has been becoming more and more popular. The analysis and control design of ramp metering based on the first order Cell Transmission Model (CTM) is one example (Muñoz et al, 2004; Gomes and Horowitz, 2006). Another example is to use a second order model for combined Variable Speed Limit and Coordinated Ramp Meter control design in (Papageorgiou, 1983, 1990), Papamichail et al (2008), and Hegyi (2005). This chapter addresses macroscopic modeling issues based on practical traffic control design considerations.

The CTM represents density dynamics. Thus the corresponding control strategy using ramp metering is to control the average density in each cell. For control design using the second order model, the density ρ and distance mean speed v are the state variables. By definition, density is a distance concept which, in principle, can be estimated by the vehicle count instantly captured by a video camera for the stretch of highway involved. However, in practice, video cameras are not easy to install and maintain if they need to provide complete coverage of the road network. Most traffic sensors in the road are inductive loops, which provide point measurements. High density installation of loop detectors would give a better estimation of density but would be cost prohibitive. It is well-known that loops, particularly in dual loop stations, provide good measurements of vehicle count in unit time, or flow. A question naturally arises: is it possible to use flow instead of density as the state variable in traffic dynamics for control design? It turns out that flow cannot be the state in a first order model, but it can be coupled with speed to form a second order model.

This chapter is organized as follows: section 3.2 is the literature review; section 3.3 deduces the flow dynamics; section 3.4 discusses the possibility for flow to be a state in a first order model, and coupled with speed dynamics to for a second order model; and section 3.5 provides conclusions about the macroscopic modeling.

3.2 Literature Review

There are at least three approaches in the literature for macroscopic traffic modeling.

(1) Based on the physics of fluid flow – traffic is considered as compressible flow. Representative work in this approach is the well-known LWR model Lighthill and Whitham (1955a, b) and Richards (1956), and later development by Newell (1993a, b, c), Daganzo (1995a, b, c) and Zhang (1998, 1999a, 1999b, 2000). A good collection and review of the kinematic wave models and its development history can be found in Gartner et al (2001).

(2) Based on driver behavior and intuitive understanding of traffic behavior such as prediction and delay. Representative work in this direction is the model by Payne (1971) and the

improvement by Papageorgiou (1983), which is called the Payne- Papageorgiou model here. It is essentially a second model with coupled density and speed dynamics. Since then, several second order models have been obtained by modification/improvement on the model. The model has been further improved in (Papageorgiou, 1990) by introducing the weaving effect due to lane changing. Since the authors intended for ramp meter control and different ramp meter strategy evaluation only, there was essentially only one control variable – the ramp meter rate. The speed dynamics were not intended to be independent. Instead, a reference speed was generated based on a static density-speed relationship – the Fundamental Diagram, and then this reference speed was input into the speed dynamics, which are coupled with the density dynamics. The density dynamics are indirectly affected through coupling with speed dynamics. In this sense, the second model is represents the dynamics of density with some driver behavior added through the speed dynamics. The theoretical model of second order was used in (Hegyi et al, 2005) for combined VSL and Ramp Metering for reducing shockwaves. A good reference is referred to (Nagel, 1998) for understanding several second-order traffic models based on fluid dynamics. The explanation is very interesting, particularly the car following model and the Payne- Papageorgiou model.

(3) The third approach is to obtain a second order model by aggregating microscopic traffic models such as a car following model (Darbha, 2001; Tyagi et al 2008). Aggregation of a set of dynamical equations must follow some rules: (a) their initial conditions must belong to the same set; (b) the dynamics should have a similar structure; and (c) some other mathematical criteria. The second order model deduced and discretized in (Tyagi et al 2008) is different from any other second order model in the literature. Zhang (1998) considered the consistency of microscopic and macroscopic models for the improvement of the second order model. The objective is to remove the upstream traffic effect on downstream flow. The first-order model is the conservation law; and the second order dynamics of speed is the conservation of momentum:

$$v_t + v v_x = -c(\rho) v_x$$

which was claimed to be deduced from the following car following model:

$$\begin{aligned} \tau(s_n(t))\ddot{x}(t) &= \dot{x}_{n-1}(t) - \dot{x}_n(t) \\ s_n(t) &= x_{n-1}(t) - x_n(t) \end{aligned}$$

$s_n(t)$ - following distance

$\tau(s_n(t))$ - driver response time

$-c(\rho) \equiv -\rho V_*^{'}(\rho) = \frac{s}{\tau(s)}$ is an introduced concept – traffic sound speed. However, the deduction simply dropped the index for individual vehicles, which is different from the principles suggested in (Darbha, 2001).

The most popularly used first order model for traffic control purpose is the CTM (Daganzo, 1994, 1995a). To understand the equivalence of this model to the first order LWR model, it is necessary to have a look at the traffic states and their units in the dynamics. The original LWR dynamics is:

$$\frac{\partial q(x,t)}{\partial x} = -\frac{\partial \rho(x,t)}{\partial t}$$

or in a difference form:

$$\frac{\Delta\left(\min\left\{v\rho, q_{\max}, v\left(\rho_J - \rho\right)\right\}\right)}{\Delta x} = -\frac{\rho(x,t+\Delta t) - \rho(x,t)}{\Delta t}$$

If the equation is discretized by introducing the concept of cell as in Daganzo (1994, 1995a), it can be written as:

$$\begin{aligned} &\rho(i,k+1) - \rho(i,k) = \frac{1}{\bar{v}(i,k)}\left[Y(i,k) - Y(i+1,k)\right] \\ &Y_i(i,k) = \min\left\{v(i,k)\cdot\rho(i,k), q_{\max}, w(i,k)\cdot\left(\rho_J - \rho(i,k)\right)\right\} \end{aligned} \tag{3.1}$$

The first equation can be equivalently represented as

$$\rho(i,k+1) = \rho(i,k) + \frac{T}{L}\left[Y(i,k) - Y(i+1,k)\right] \tag{3.2}$$

where i is the cell index and k is the time index;
$\rho(i,k)$ – density in cell i at time period k;
$v(i,k)$ – distance mean speed in cell i at time period k;
$w(i,k)$ – shockwave back-propagation speed in cell i at time period k;
$q_{\max}$ – maximum flow of the cell to be identified as a constant parameter – the capacity;
ρ_J – jam density, a known constant parameter.

It is noted that model (3.1) is not a closed dynamical system since it contains speed variable $v(i,k)$ which is not supposed to be in the dynamics although the shockwave speed $w(i,k)$ is known to be very close to constant for traffic with high enough density. To overcome this difficulty, the Fundamental Diagram (FD) is assumed, which is a static flow-density relationship $q = q(\rho)$ or speed-density relationship $v = v(\rho)$. Once the relationship is modeled for each cell, the first and the third term in the expression of $Y_i(i,k)$ (3.1) can be evaluated.

3.3 Flow Dynamics

Our purpose is to deduce a flow dynamics model suitable for traffic control purposes. First, the flow dynamics is equivalently deduced from the LWR model. The control problem is formulated including the controllability of the model etc.

Flow Model Derivation

This part deduces the mainline flow model based on the LWR model represented as a first order wave equation:

$$\begin{aligned}&\frac{\partial \rho(x,t)}{\partial t}+\frac{\partial q(x,t)}{\partial x}=0\\&\rho(x,t)=\frac{q(x,t)}{v(x,t)}\end{aligned} \tag{3.3}$$

under the assumption that $v(x,t)\neq 0$. In fact, this assumption guarantees that the transformed model is equivalent to the original model (3.1). The case $v(x,t)=0$ will be treated separately later.

$$\frac{\partial \rho(x,t)}{\partial t}=\frac{\partial\left(\dfrac{q(x,t)}{v(x,t)}\right)}{\partial t}=\frac{\dfrac{\partial(q(x,t))}{\partial t}v(x,t)-\dfrac{\partial v(x,t)}{\partial t}q(x,t)}{v^2(x,t)}$$

Replacing it in the wave equation (3.1), it becomes:

$$\frac{\partial(q(x,t))}{\partial t}v(x,t)-\frac{\partial v(x,t)}{\partial t}q(x,t)=-\frac{\partial q(x,t)}{\partial x}v^2(x,t) \tag{3.4}$$

or equivalently:

$$\frac{\partial(q(x,t))}{\partial t}=\frac{\partial v(x,t)}{\partial t}\frac{q(x,t)}{v(x,t)}-\frac{\partial q(x,t)}{\partial x}v(x,t) \tag{3.5}$$

if $v(x,t)\neq 0$. Now, its corresponding difference equation can be written as

$$\frac{q(x,t+\Delta t)-q(x,t)}{\Delta t}=\frac{\left[v(x,t+\Delta t)-v(x,t)\right]}{\Delta t}\frac{q(x,t)}{v(x,t)}-\frac{q(x+\Delta x,t)-q(x,t)}{\Delta x}v(x,t)$$

It can be discretized under the following convention and assumption:

- The cell index is i, which represents the cell index with $i+1$ as the index of the cell immediately downstream of cell i;
- The length of cell i is L_i;

- Speed and flow are constants in each cell;
- Time increment index is k with $t = k \cdot \Delta T$

$$q_i(k+1) = q_i(k) + \left[v_i(k+1) - v_i(k)\right]\frac{q_i(k)}{v_i(k)} - \frac{\Delta T}{L_i}\left[q_{i+1}(k) - q_i(k)\right]v_i(k) \tag{3.6}$$

If we further assume that:

$$\frac{\left[v_i(k+1) - v_i(k)\right]}{v_i(k)} \approx \frac{\left[v_i(k) - v_i(k-1)\right]}{v_i(k-1)} \tag{3.7}$$

i.e. the previous step relative speed variation is used in place of the next step relative speed variation , it is obtained that

$$q_i(k+1) = \left[1 + \frac{v_i(k) - v_i(k-1)}{v_i(k-1)}\right]q_i(k) - \frac{\Delta T}{L_i}\left[q_{i+1}(k) - q_i(k)\right] \tag{3.8}$$

Singularity will not happen due to the assumption at the beginning that $v(x,t) \neq 0$ which means that $v_i(k) \neq 0,$ for any i and k.

In the case of $v(x,t) = 0$,

$$q(x,t) = 0$$

Thus the following variable structure model is reached:

$$q_i(k+1) = \begin{cases} \left[1 + \dfrac{v_i(k) - v_i(k-1)}{v_i(k-1)}\right]q_i(k) - \dfrac{\Delta T}{L_i}\left[q_{i+1}(k) - q_i(k)\right]v_i(k), & \text{if } v_i(k-1) \neq 0; \\ 0, & \text{if } v_i(k-1) = 0. \end{cases} \tag{3.9}$$

To Formulate the Control System

To take into account the interaction between the mainline and the onramp/off-ramp, the first part in model (3.9) should be modified as when $v_i(k-1)$

$$q_i(k+1) = \left[1 + \frac{v_i(k) - v_i(k-1)}{\max\left\{v_i(k-1), \sigma\right\}}\right]q_i(k) - \frac{\Delta T}{L_i}\left[q_{i+1}(k) - q_i(k)\right]v_i(k) + r_i(k) - s_i(k) \tag{3.10}$$

$0<\sigma<<1.0$ is used to avoid singularity. $r_i(k)\geq 0$ is the flow into the mainline from onramp in time step k if applicable, which is a **control variable** for ramp-metering, that the traffic control engineer can manipulate. $s_i(k)\geq 0$ is the flow out of the mainline from off-ramp in time step k, which is to be measured/estimated as a system parameter.

In practical implementation, it is necessary to take into consideration the time interval difference of aggregation for flow and for metering. Suppose the time interval for flow aggregation is ΔT as above; and the metering time interval at the onramp is Δt. Then the following condition is to be satisfied by the onramp flow and metering rate:

$$\begin{aligned} & r(k)\cdot\Delta T = r^{(c)}(k)\cdot\Delta t \\ \text{or}\quad & r(k)=\frac{\Delta t}{\Delta T}\cdot r^{(c)}(k) \end{aligned} \tag{3.11}$$

where $r^{(c)}(k)$ is the practical metering flow rate with respect its own timer. Thus the model (3.9) needs to be modified as

$$q_i(k+1)=\left[1+\frac{v_i(k)-v_i(k-1)}{\max\{v_i(k-1),\sigma\}}\right]q_i(k)-\frac{\Delta T}{L_i}\left[q_{i+1}(k)-q_i(k)\right]v_i(k)+\frac{\Delta t}{\Delta T}r_i^{(c)}(k)-s_i(k) \tag{3.12}$$

which contains both flow and speed. Therefore it needs further treatment to represent a dynamical system.

3.4. An Equivalent Second Order Model

It is necessary to investigate how the flow dynamics with speed variable involved is used for control. Two possibilities are considered: the first order model and the second order model.

First Order Model

The CTM could be used for ramp metering control (Gomes and Horowitz (2006)) – to adjust the onramp in-flow rate for controlling the average density in a cell. An immediate question is whether we can have a flow dynamics model that is equivalent to the CTM. The answer to this question is negative. The CTM and (3.10) are based on the same LRW model. The CTM derivation was based on the assumption of the Fundamental Diagram, i.e., a static relationship between flow and density and therefore a speed-density relationship which is usually monotone decreasing and thus is well defined. Based on this, the speed variable in the discretized LWR model can be eliminated. However, the speed-flow relationship does not have an inverse as shown in the following figure obtained for Berkeley Highway Laboratory data (Figure 3.1). A typical curve fitting of such data results in a curve as in Figure 3.2, in which one flow corresponds to two speed values. It is thus concluded that the first order flow dynamics model cannot be established in a sensible way as the CTM model.

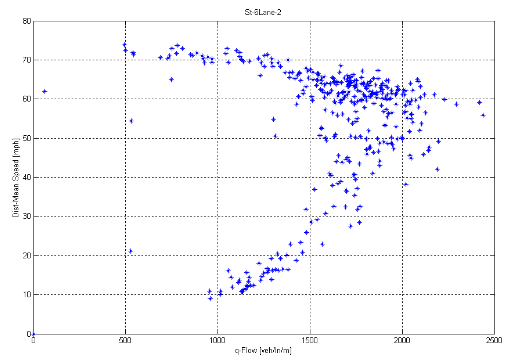


Figure 3.1 Scatter plot of speed-flow from BHL data, 07/01/2007

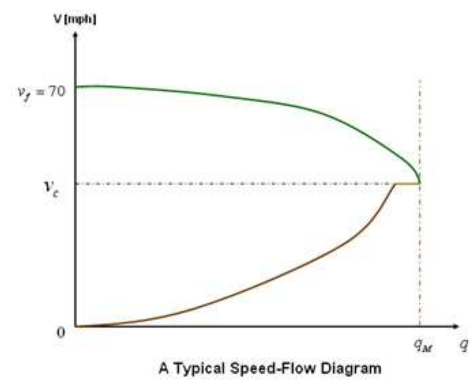


Figure 3.2 A typical model of speed-flow diagram

Second Order Model

A feasible application, however, is to add speed dynamics to the flow dynamics to represent second order dynamics, such as in the second order model of Payne (1971), in which the speed dynamics deduction was based on the following assumptions:

- Distance mean speed $v(x,t)$ at space-time point (x,t) depends on the density downstream with distance increment Δx ;
- There was a time delay due to driver's response in speed adjustment: $v(x+\tau,t)$ was used instead;
- Driver can predict the traffic speed of the next cell; although this assumption was not necessarily true in the past, it is more reasonable in a VSL and Coordinated Ramp Metering strategy since the traffic situation downstream is supposed to be measured and used as input to the control strategy, although the driver would not perceive it directly. This process implicitly helps the driver incorporate traffic conditions downstream;
- There is a static relationship between speed and density described as

$$v(x,t+\tau)=V\left(\rho(x+\Delta x,t)\right) \tag{3.13}$$

which could be interpreted as: the density in the $v-\rho$ relationship of the FD has been predicted ahead over distance Δx, but the average driver's response has been delayed by τ in time. Using Taylor series expansion to both sides of the equation with respect to *t* and *x* respectively and discretizing, one can reach the following speed dynamics.

$$v_i(k+1)=v_i(k)+\frac{T}{\tau}\left(V(\rho_i(k))-v_i(k)\right)-\frac{T}{L}v_i(k)\left(v_{i-1}(k)-v_i(k)\right)-\frac{\nu T}{\tau L}\frac{\rho_{i+1}(k)-\rho_i(k)}{\rho_i(k)+\kappa} \tag{3.14}$$

where T – time step length
L – cell length
τ, ν, κ are parameters to be calibrated from field data.

The terms of the right hand side of the model could be interpreted as follows:

(1) The 1st - relaxation term: It is a high gain filter: the driver is trying to achieve the desired speed $V(\rho_i(k))$ - a **control variable**, where τ is a high gain filter from a dynamic system viewpoint. It can be interpreted as the average response delay of the driver to the desired speed. The definition of the desired speed is critical to reflect the driver behavior.

(2) The 2nd - convection term: the effect of the traffic flowing into the downstream cell from upstream cell; i.e., the speed increase/decrease caused by in-flow and out-flow vehicle speeds. It can be modified by adding a factor $sat\left(\rho_{i-1}/\rho_i\right)$ where $sat(\cdot)$ is the saturation function to address the driver speed change with respect to density variation between the two consecutive cells (Cremer and Papageorgiou (1981)).

(3) The 3rd - density gradient term: when downstream density increases/decreases, the speed in the current cell will decrease/increase;

$$-\frac{\nu T}{\tau L}\frac{\rho_{i+1}(k)-\rho_i(k)}{\rho_i(k)+\kappa}=-\frac{1}{\tau}\left(\frac{\nu T}{L}\frac{\rho_{i+1}(k)-\rho_i(k)}{\rho_i(k)+\kappa}\right)$$

where τ is a high gain filter representing the time delay for the driver's response to the perception of the traffic density (basically, what each driver could observe is the inter-vehicle distance in the immediate vicinity (which could be interpreted as the driver version of *local density*); ν is a sensitivity factor. The part in the bracket expresses the effect of downstream cell density: the higher the downstream density, the lower the speed for the current cell. $\rho_i(k)$ in the denominator is for normalization. Parameter $\kappa > 0$ is added for two purposes:

- To force the model only to work for medium to high density
- To avoid singularity or abnormal behaviors of the model at low density.

The physical meaning of the three terms including the parameters was also explained in details related to driver behavior in (Cremer and Papageorgiou 1981). Those explanations could be used as the basis for parameter identification.

3.5 Model reduction

Since $V(\rho_i(k))$ is basically the speed control parameter to be designed, it could be parameterized with any other value instead of density $\rho_i(k)$ or even without parameterization at all. For example, it could be parameterized with flow $q_i(k)$.
Doing this is just a matter of coordinate transformation to understand how the control design would affect the shape changing of the FD.

Now (3.2) can be equivalently written as

$$v_i(k+1)=v_i(k)+\frac{T}{\tau}(V-v_i(k))-\frac{T}{L}v_i(k)(v_{i-1}(k)-v_i(k))-\frac{\nu T}{\tau L}\left[\frac{q_{i+1}(k)\cdot v_i(k)}{q_i(k)\cdot v_{i+1}(k)+\kappa_1}-1\right] \quad (3.15)$$

where κ_1 is a new system parameter to be calibrated using field data. Its function is to avoid singularity.

Now (3.10) and (3.15) form a well-defined second order dynamical system with state variables $(q_i(k),v_i(k))$ and control parameters $(r_i^{(c)}(k),V)$ - the ramp meter rate and the desired speed limit. It is easy to see that the system is controllable.

It is important to note that the second order model (3.10) and (3.15) are similar to the Payne-Papageorgiou model in principle. This can be observed from the derivation process above. However, the significant difference here is that there is no further parameterization in the control variables; i. e., V is a free design parameter. This is a significant difference in the following sense:

- There is no Fundamental Diagram assumption in the model anymore, in contrast to the model used by Papageorgiou (1990), Papamichail (2008), and Hegyi et al (2005);
- The control variable appears linearly, which is more convenient for design;
- Fundamental Diagram calibration often leads to large error, which leads to significant model mismatch. Dropping the FD assumption relieves this problem.

The application of these simplified speed dynamics in control design is underway.

3.6 The Fundamental Diagram and Model Validation

Macroscopic models usually represent traffic as a continuous fluid, described by a few aggregate variables: flow, density and mean speed. In contrast to macroscopic models, microscopic traffic flow models simulate single vehicle-driver units, thus the dynamic variables of the models represent microscopic properties like the position, acceleration rate, deceleration rate and velocity of a single vehicle. While the behavior of individual drivers is ignored, we are only concerned about the behavior of aggregated traffic variables. Macroscopic simulation tools try to replicate aggregate traffic behavior, and are suitable for rapid evaluation of multiple test scenarios and control strategies as they are easier to integrate and calibrate.

Lighthill and Whitham made an early influential contribution to the macroscopic theory of traffic (Lighthill 1955). Their first-order model includes the fundamental equation for traffic flow and the continuity equation. To derive the model, we consider a segment of infinitesimal length along a roadway segment. Let $\rho_{j,k}$ denote the average aggregate density in units of (veh/mile), i.e., vehicles per unit length on link *j* during time interval *k*, and $v_{j,k}$ denote the average speed of vehicles on link *j* during time interval *k*. Also the traffic flow $q_{j,k}$ is defined as the numbers of vehicles exiting link *j* during time interval *k*. By definition, the relationship existing among the above three fundamental variables is exactly:

$$q_{j,k} = \rho_{j,k} \times v_{j,k} \tag{3.16}$$

as in fluid dynamics. In spite of this relationship, intuition and driving experience on freeways suggest that $v_{j,k}$ is directly influenced by the traffic density. As the number of vehicles increases in the roadway section the average speed monotonically decreases, and vice versa. This observation has motivated a simple traffic flow model in which density and speed are related by a static, monotonically-decreasing function

$$v_{j,k} = v_e(\rho_{j,k}) \tag{3.17}$$

Several functional forms for $v_e(.)$ can be found in the literature (Papageorgiou, 1983; Gerlough, 1975; Castillo, 1995). Greenshields (Greenshields, 1934) proposed a linear relationship between flow and density:

$$v_e(\rho_{j,k}) = v_{free}\left(1 - \frac{\rho_{j,k}}{\rho_{jam}}\right) \tag{3.18}$$

where v_{free} is the free-flow speed and ρ_{jam} is the jam density, i.e., the density at which the speed is zero. Another family of nonlinear speed-density characteristics has been derived from the car-following model which is a generalization of the Greenshields model (Pipes, 1967).

$$v_e(\rho_{j,k}) = v_{free}\left[1 - \left(\frac{\rho_{j,k}}{\rho_{critical}}\right)^l\right]^m \tag{3.19}$$

The model validation procedure aims at enabling the whole freeway network model to represent traffic conditions with required accuracy. Quantitative model validation aims to estimate model parameters through a well-defined straightforward procedure, while qualitative model validation aims to represent traffic conditions for the whole corridor or network and test whether the model can accurately capture the corridor-wide dynamics of traffic congestion (Kotsialos, 2002). Both quantitative analysis and qualitative analysis are adopted to validate traffic models in this study, and the validation flowchart can be found in Figure 3.3.

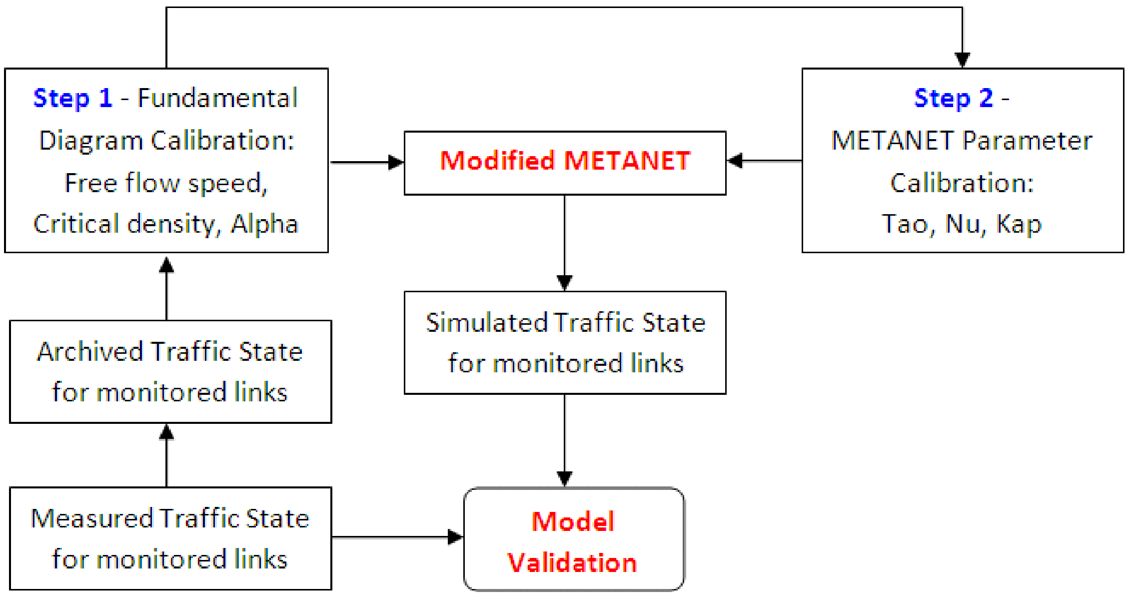


Figure 3.3 Flowchart of modified METANET model validation

To validate the proposed modified METANET model empirical data from the Berkeley Highway Laboratory (BHL) system have been used. BHL is a test site that covers 2.7 miles of I-80 eastbound immediately east of the San Francisco-Oakland Bay Bridge in California, which can be seen in Figure 3.4. Each detector station is dual loop, providing 60 Hz event data on individual vehicle actuations. Based on the raw BHL event data, accurate aggregated flow and speed information can be extracted. After the calibration procedure, the following parameter values are adopted: $\tau = 0.02$, $\nu = 8.5$, , $\kappa = 32$. The starting time of model validation is 12:00 am on March 31, 2009, corresponding to the time index 0 on the X axis, and the ending time of model validation is 12:00 am on April 1, 2009, associated with the time index 1440.

Because of BHL system errors, the data from 2:45 am to 3:30 am were not archived. Since it was in the early morning, the flow was pretty low and speed was at the free flow speed level, so the missing data did not impact the comparison results much. Figure 3.5 shows the comparison of results between METANET and our proposed modified METANET model for cell 5, which is located between station 4 and station 5. Figure 3.5.a is from the original METANET model, while Figure 3.5.b is from the modified METANET model. The red curves in Figure 3.5 stand for the actual measurements from BHL data, and the green curves represent the model simulation outputs. Figure 3.6 compares the simulated speed results between the METANET and modified

METANET models for six consecutive cells, and only the congestion time period 3:00 pm-6:00 pm is considered for comparison in this study. The red curves in Figure 3.6 stand for the actual measurement from BHL data, and the blue curves represent the model simulation outputs. From the point of view of qualitative analysis, the modified METANET can more effectively catch the speed drop and recovery during the congestion period. From the point of view of quantitative analysis, during the congestion time period, the average simulated speed error from the original METANET model was 25 mph, while the average simulated speed error from our proposed METANET model was 8 mph. There is no significant difference between these two models in free flow.

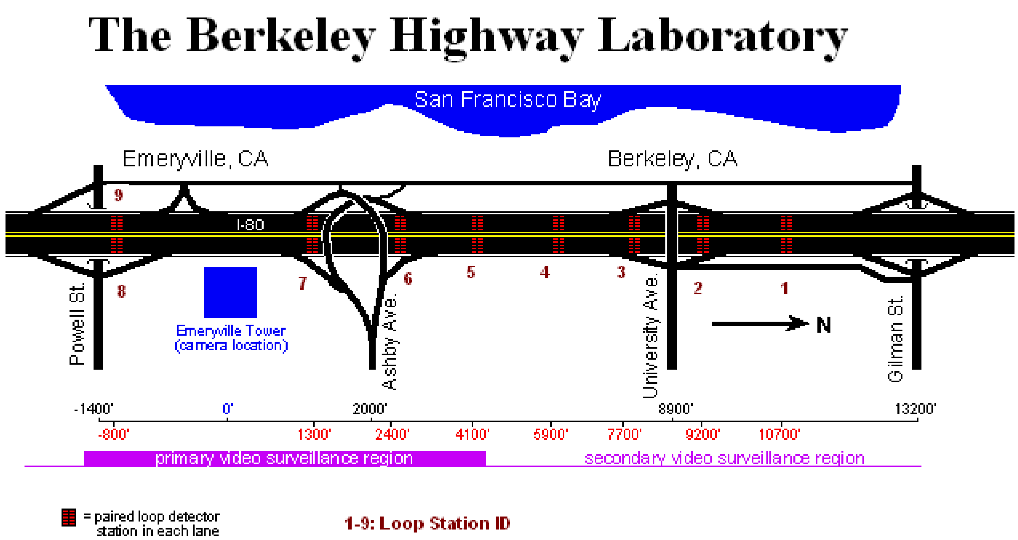
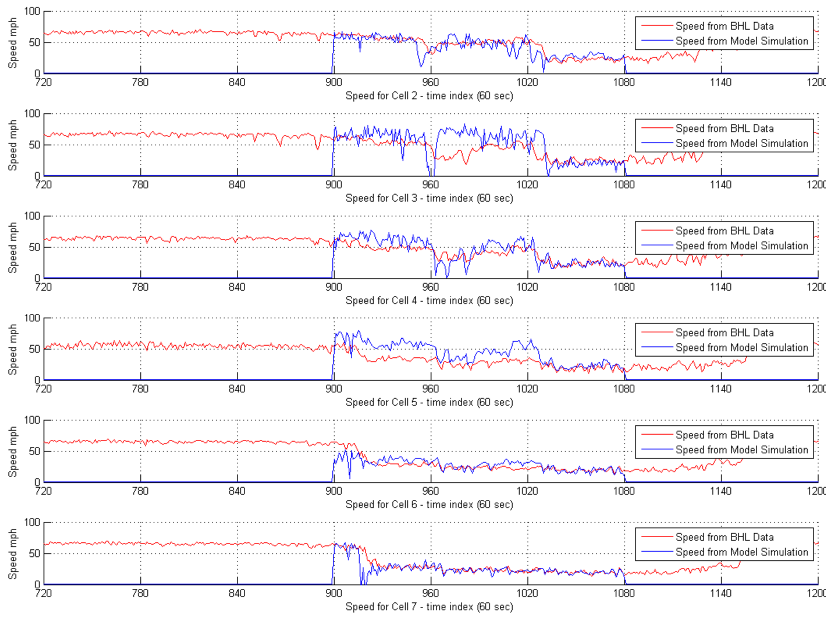


Figure 3.4 Studied freeway stretch – BHL covered area

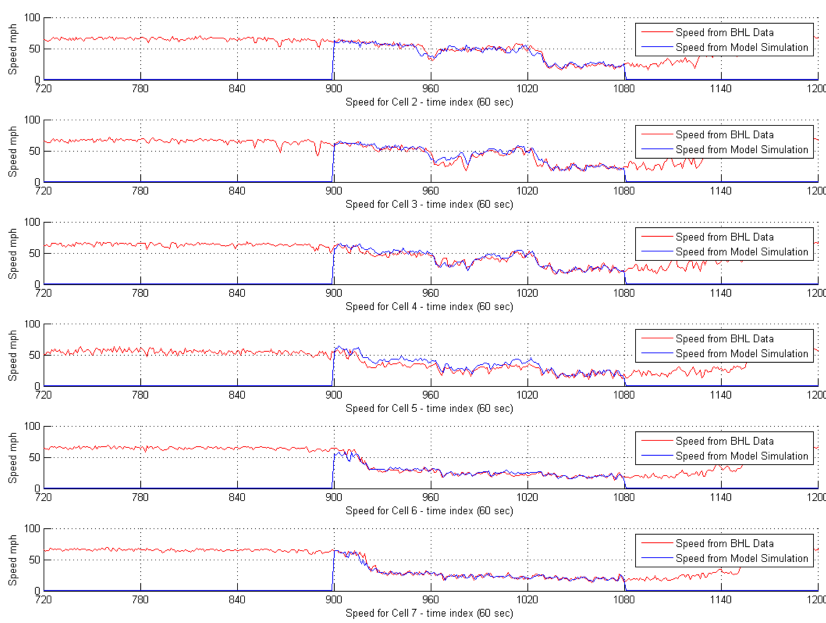
a. METANET simulation output and actual BHL measurements

b. Modified METANET simulation output and actual BHL measurements

Figure 3.5 Comparison between METANET and modified METANET for Cell 5



a. METANET simulation output and actual BHL measurements



b. Modified METANET simulation output and actual BHL measurements

Figure 3.6 Comparison of simulated speed between METANET and modified METANET for six consecutive cells

3.7 Onramp Dynamics and Constraints

It is determined by onramp demand and queue dynamics, which are the same as used by Papamichail (2008):

$$w_m(k+1) = w_m(k) + T \cdot \left[d_m(k) - q_{m,o}(k) \right]: \quad \text{queue length dynamics}$$

$$q_{m,o}(k) = r(k)\hat{q}_{m,o}(k) \Rightarrow r(k) = \frac{q_{m,o}(k)}{\hat{q}_{m,o}(k)}$$

$$\hat{q}_{m,o}(k) = \min\left\{ \hat{q}_{m,1}(k), \hat{q}_{m,2}(k) \right\}$$

$$\hat{q}_{m,1}(k) = d_m(k) + w_m(k).T: \quad \text{effected by demand and queue length}$$

$$\hat{q}_{m,2}(k) = Q_m \cdot \min\left\{ 1, \frac{\rho_{\max} - \rho_{m,1}(k)}{\rho_{\max} - \rho_{cr}(k)} \right\}; \quad Q_m - \text{ onramp flow capacity}$$

Parameters to be determined in this part include:

- $d_m(k)-$ the demand for onramp *m*
- $Q_m -$ flow capacity for onramp *m*
- $\rho_{\max} -$ maximum density of the network
- $\rho_{cr}(k)-$ the critical density

Comment: The following relationship does not make sense:

$$\hat{q}_{m,1}(k) = d_m(k) + w_m(k).T$$

since:

$d_m(k)-$is demand flow (#veh/hr)

$w_m(k)-$the number of vehicles stored in onramp *m*

In order to make sense, it should be modified as:

$$\hat{q}_{m,1}(k) = d_m(k) + \frac{w_m(k)}{T}$$

Since the ramp meter rate is determined by the control strategy, it is more reasonable to put this in the objective function; i.e., to add the following quadratic term for penalty on the queue length in the objective function:

$$\sum_{m=0}^{N} w_m^2(k)$$

This added term will address the equity issue in practice. To address the ramp flow capacity limit and the receiving capacity of the immediate downstream, the $\hat{q}_{m,2}(k)$ part can be equivalently formulated as two linear constraints:

$$q_{m,o}(k) \le Q_m$$

$$q_{m,o}(k) \le \frac{\rho_{\max} - \rho_{m,1}(k)}{\rho_{\max} - \rho_{cr}(k)}$$

In this way, the constraints are still linear and the objective function is still quadratic.

So the eventual onramp dynamics and constraints involved are the following

$$\begin{aligned}
& w_m(k+1) = w_m(k) + T \cdot \left[d_m(k) - q_{m,o}(k) \right] \\
& 0 \le w_m(k+1) \le L_m^{(r)} / \rho_J \\
& q_{m,o}(k) \le Q_m \\
& q_{m,o}(k) \le \frac{\rho_{\max} - \rho_{m,1}(k)}{\rho_{\max} - \rho_{cr}(k)}
\end{aligned}$$

which can be used for control problem formulation.

3.8 Concluding Remarks

This chapter, from a practical point of view, considers the possibility of using traffic flow instead of density as the state variable for traffic control purpose. The reason to do so is that flow measurement with point sensors such as inductive loop detectors, which are the dominant sensors used in the highway traffic network in California and nationwide, can be reasonably accurate but a good density estimation is very costly if not impossible.

The flow-speed-density relationship is used for coordinate transformation in the first order LWR model, which is common in almost all first order and second order models – the conservation of vehicle numbers. Based on that, the possibility of establishing a first order model with flow as state variable has been investigated. It turns out that one cannot establish a flow dynamics counterpart of the CTM due to non-existence of the inverse function of the speed-flow relationship – an alternative expression of the Fundamental Diagram.

However, the flow dynamics coupled with the speed dynamics such as in the Payne-Papageorgiou model, establish an equivalent second-order model with flow and speed as state variables. This second order model could potentially be used for a combined Variable Speed Limit and Coordinated Ramp Metering design and application with point sensors such as inductive loops and Sensys sensors.

We further simplified the speed dynamics used in most previous work by removing the re-parameterization (essentially removing the assumption of the Fundamental Diagram), which is believed to be a great benefit to modeling and control design as well as practical application.

Model analysis for dynamical behavior, validation, simulation using field data, and application to traffic control are the research topics of the next steps.

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Chapter 4 Microscopic Simulation

4.1 Relationship of Microscopic to Macroscopic Simulation

The relationship between the microscopic simulation described in this chapter and the macroscopic simulation described in Chapter 3 is depicted in Figures 4.1 and 4.2 below.

Microscopic and macroscopic traffic simulations are usually run separately. Microscopic simulations can provide qualitative evaluation of the impact of driver behavior on traffic flow. With appropriate underlying microscopic models such as vehicle following and lane changing models, the microscopic simulation should replicate traffic flow in the sense that the aggregated outputs coincide with observed traffic state parameters (mean speed, density and flow) from the aggregation of field data measured by sensors. If this is the case, then the data aggregated from the simulation can be used to represent traffic dynamics for macroscopic traffic model validation, system analysis, control design, and control validation. Proposed traffic control strategies such as CRM and VSL can be applied to the microscopic model to affect the driver behavior, and eventually affect the traffic flow to achieve the expected performance. The corresponding performance of the controller can thus be evaluated based on macroscopic traffic data simulated and aggregated from the microscopic simulation outputs. This approach could potentially save much effort before any field test, which is critical in practice. Figure 4.1 shows how the two types of simulation systems should be combined for such a purpose.

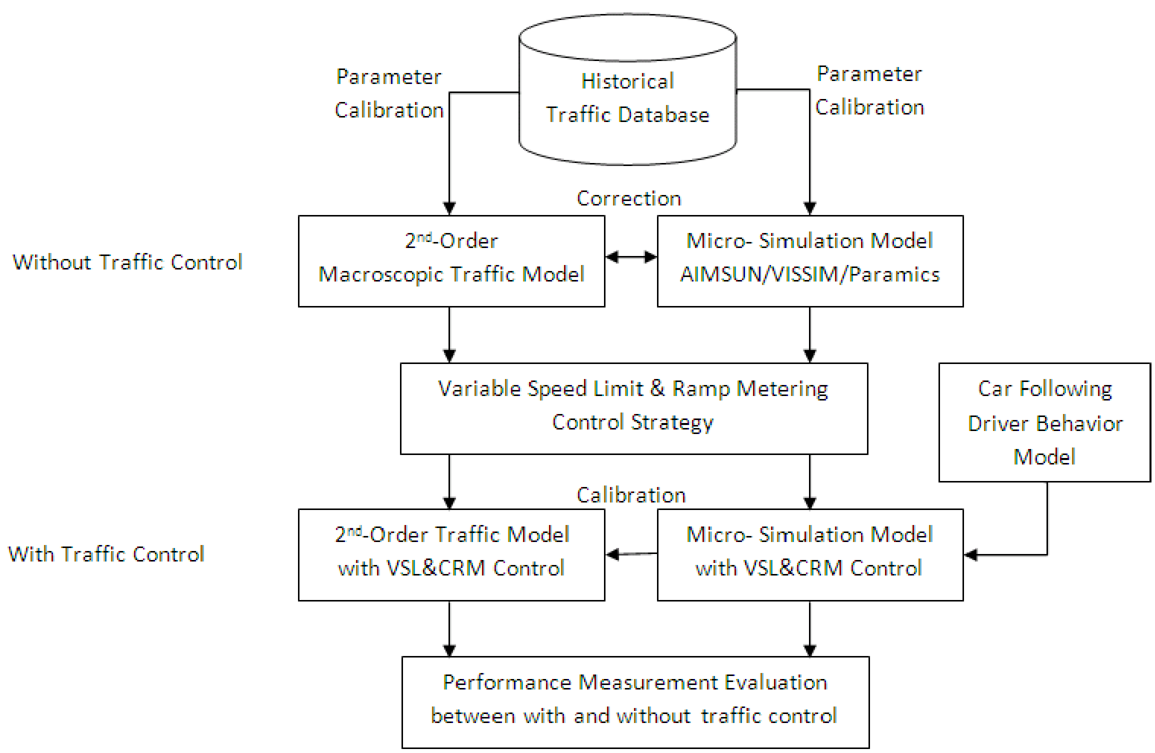

Figure 4.1 Flowchart 1 of macroscopic and microscopic simulation implementation

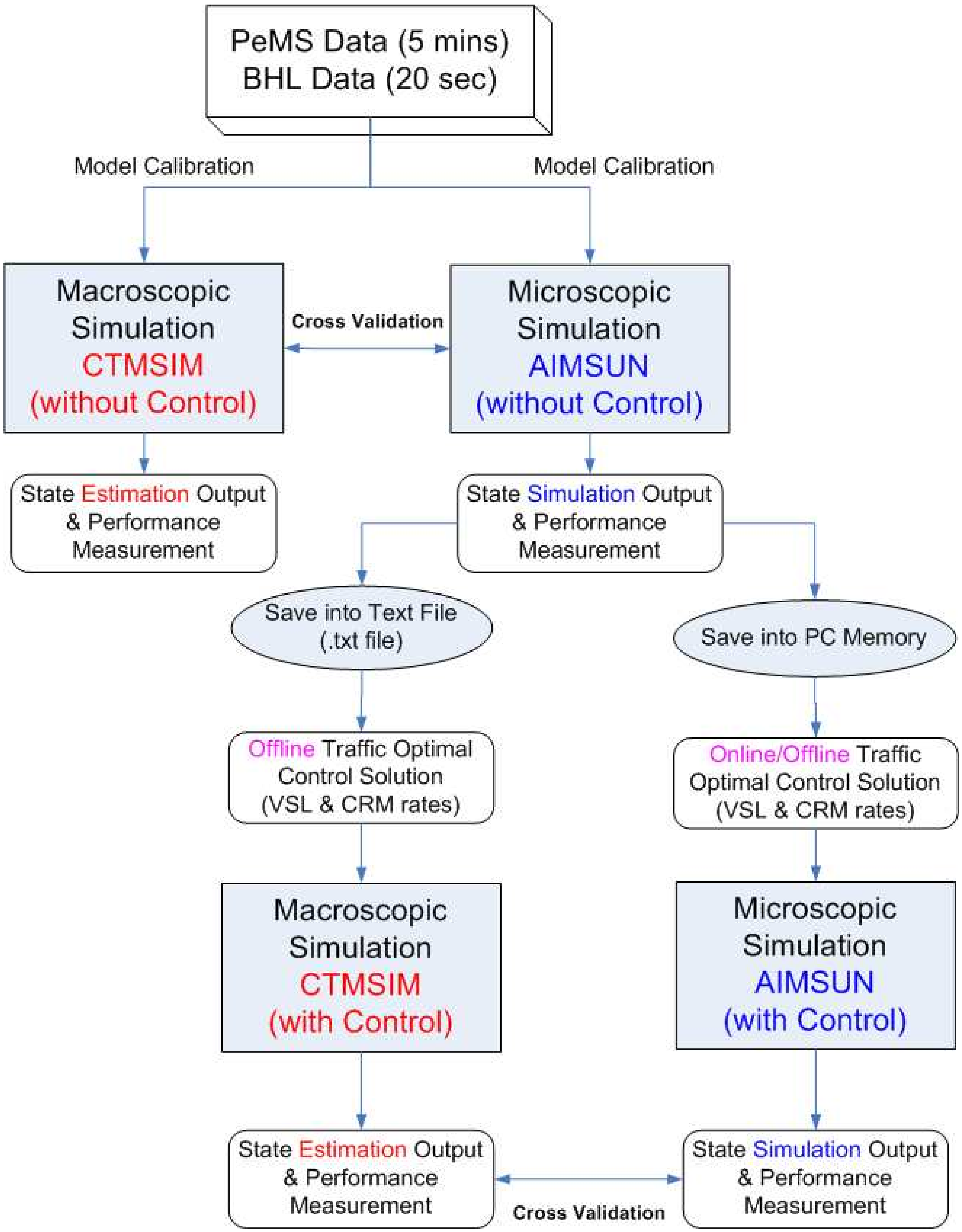

Figure 4.2 Flowchart 2 of macroscopic and microscopic simulation implementation

4.2 Microscopic Simulation

4.2.1 Introduction of Aimsun

Aimsun is a transportation simulation environment developed by TSS. It contains microscopic and mesoscopic simulators, dynamic traffic simulator, and macroscopic and static assignment models. It also offers extended tools for advanced investigation, like the Aimsun SDK (Software Development Kit), Aimsun API, and Aimsun MicroSDK. We use the Aimsun Microscopic Simulator, API, and microSDK in this project.

4.2.1.1 Aimsun Microscopic Simulator

Aimsun Microscopic Simulator allows construction of traffic networks, including for example, urban network, freeways, arterials or combinations of these networks. For a simulation network, the most important parts are the geometry of the roads, the traffic demand and the signal control plan.

In Aimsun, the geometry of the network is defined by a set of sections and nodes. In the section definition, the information includes the number of lanes, lane width, reserved lanes (HOV or public transportation), the maximum speed, and so on. In the nodes, the user should define the turning movements and speeds within the node, signal groups to control the movements, and give way priority. Aimsun is able to load background images to help construction of the road geometry. The user can also place detectors or VMS (Variable Message Signs) in the section. At each detector, the user can access information about speed, density, headway, occupancy, and vehicle count of different vehicle types. VMS are used to post the instructions for driving.

There are two ways to define the traffic demand in Aimsun. One is through the O/D matrix, and the other is through specifying traffic flows at the entrance sections and turning percentages at the nodes. The generation of vehicles can follow an exponential distribution, uniform, normal, or constant headway, or as-soon-as-possible mode, or external mode. Aimsun allows user-defined types of vehicles and classes of vehicles. For each vehicle type, the user can give the information about length, width, maximum desired speed, maximum acceleration and deceleration and so on, to define the behavior (car, bus, pedestrian, or bicycle). For vehicle class, vehicles can be assigned to HOV, public transportation, or other user-defined classes.

Policies and strategies are applied to manage the traffic in the network. Policy refers to a specific type of action applied to the network, such as closing a lane (or prohibiting a specified type of vehicle from using that lane), changing the maximum speed for a section, forcing turning, rerouting, and generating incidents in the section. One or more policies form a control strategy. The user can implement ramp metering in Aimsun by changing the duration of green time of the traffic signal, or controlling the flow (vehicle count) into the mainline, or defining the time delay for the vehicle merging into the mainline.

4. 2.1.2 Aimsun API

The Aimsun API module is an interface that allows external applications to access the internal data of Aimsun during simulation. The user can obtain or sometimes modify the information about the vehicle, detector, VMS, and control in the system. It offers functions to access the traffic conditions on the road, such as statistics about the system, or the information about a section, a vehicle type, or a specific vehicle. The API (Application Program Interface) is the bridge between the user and the simulation package: (a) the simulation data such as detector measurement (both raw data and aggregated data) can be obtained there as output; (b) some system/model parameters built into the default model/package can be changed to fit the simulation of the user; (c) the API also enables the user to change the control plan, like set a new speed limit, change the metering policy, or simulate the generation of an incident.

4. 2.1.3 MicroSDK

The Microscopic Model SDK is the tool to implement new behavior models in Aimsun simulation, replacing the default model in Aimsun. The default driver model provided by Aimsun is based on the Gipps model. However, this model may not be appropriate for representing driver behavioral responses to VSL or for more general driver behavior in congested traffic. To address these more complicated phenomena, the user can introduce new driver behavior by the plug-in by the interface offered in MicroSDK. The plug-in is written in C++ as a DLL file. By MicroSDK, the user is able to obtain the dynamics of the vehicle, the information about upstream or downstream vehicles, and traffic conditions or geometry of the road, and further specify the behavior of the vehicle in terms of new speed or new position, or changing lane. During each simulation step, Aimsun calls the functions in the plug-in and updates the driver behavior based on the user-defined model. Usually, MicroSDK is used together with Aimsun API.

4.3 Network Geometry Construction

We built a simulation network covering I-80 westbound from Cutting Blvd to the Bay Bridge, and extending to W MacArthur Blvd for I-580 and the Frontage Rd for I-880, including the connector to I-580 near Buchanan St. The network was constructed in the following steps.

1) Obtain Google map image of the investigated area, load it and set the appropriate scale in Aimsun as the background image.

2) Place the sections and nodes according to the image, set the number of lanes, lane width, reserved HOV lane and speed limit, draw the solid line for constructing a road and specify the turning at the nodes. After comparing the simulation network and the Google map, the error in the length of the sections was less than 2%. Part of the network is shown as in Figure 4.3.

3) Add the PeMS and BHL detectors into the network. Some additional detectors and ramp meters, and variable message signs for control are also placed where necessary.

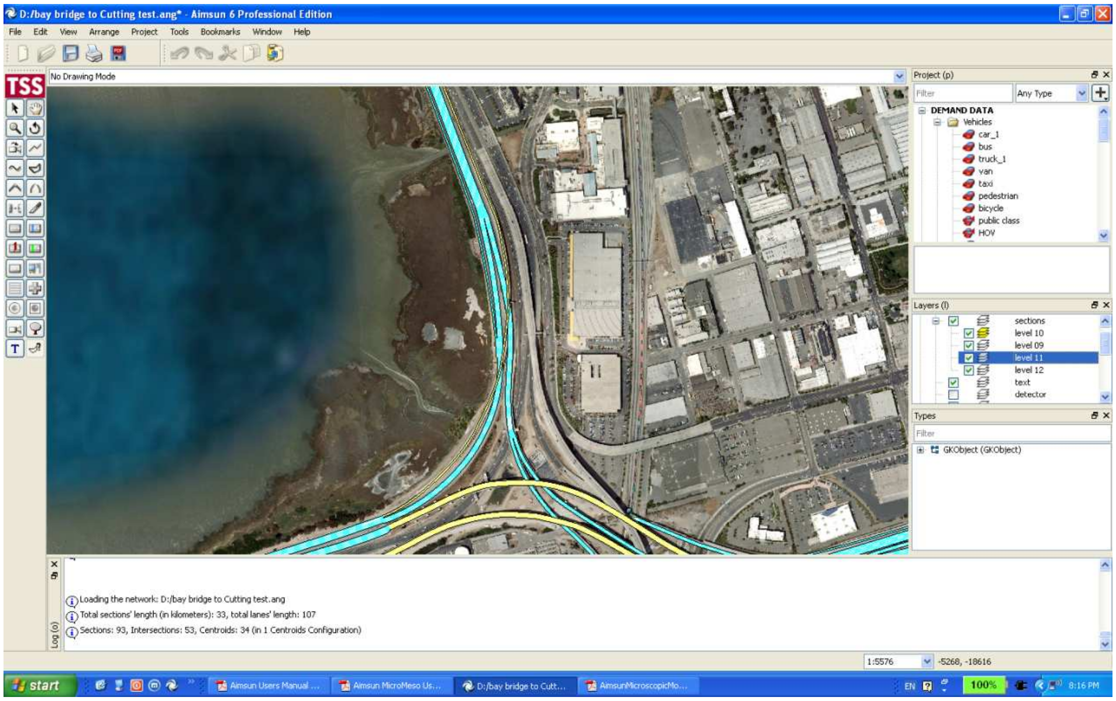

Figure 4.3 Google Map View of Part of the Network

4.4 OD Table Calculation

We generate the OD matrix for this network based on the information from the I-80 Integrated Corridor Management Project (ICMP). The I-80 ICMP uses a two-direction network including both I-80 (from the Carquinez Bridge to Bay Bridge) and San Pablo Ave. The traffic in this network is generated in the local streets near San Pablo Ave, not in the I-80 west sections we investigate. So we calculate the traffic demand of the part we are interested in. The OD matrix is constructed by the following rules:

1) For a vehicle which starts on San Pablo Ave and travels along I-80 westbound, it uses the nearest onramp to enter I-80. If the distances to the two onramps are nearly the same, it has an equal probability of using each onramp, as shown in Figure 4.4.

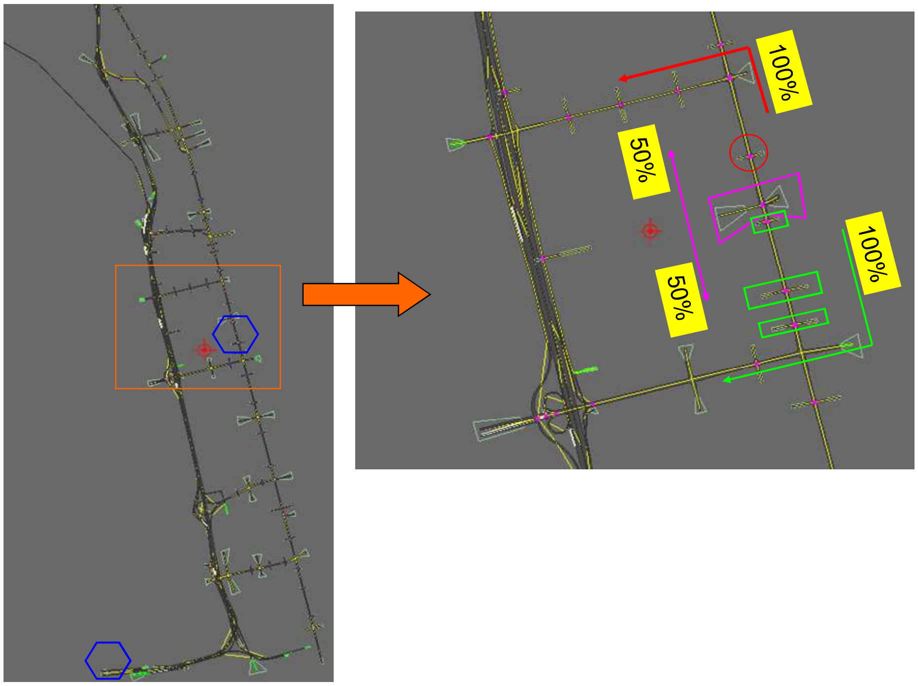

Figure 4.4 The selection of the onramp for a trip originating in a local neighborhood

2) For a vehicle traveling on I-80 from upstream of Cutting Blvd to downstream of it, and needing to exit to San Pablo Ave, it exits at the off-ramp which is nearest to the destination on San Pablo Ave. If there are two off-ramps that have the same distance, it chooses these off-ramps with equal probability as shown in Figure 4.5.

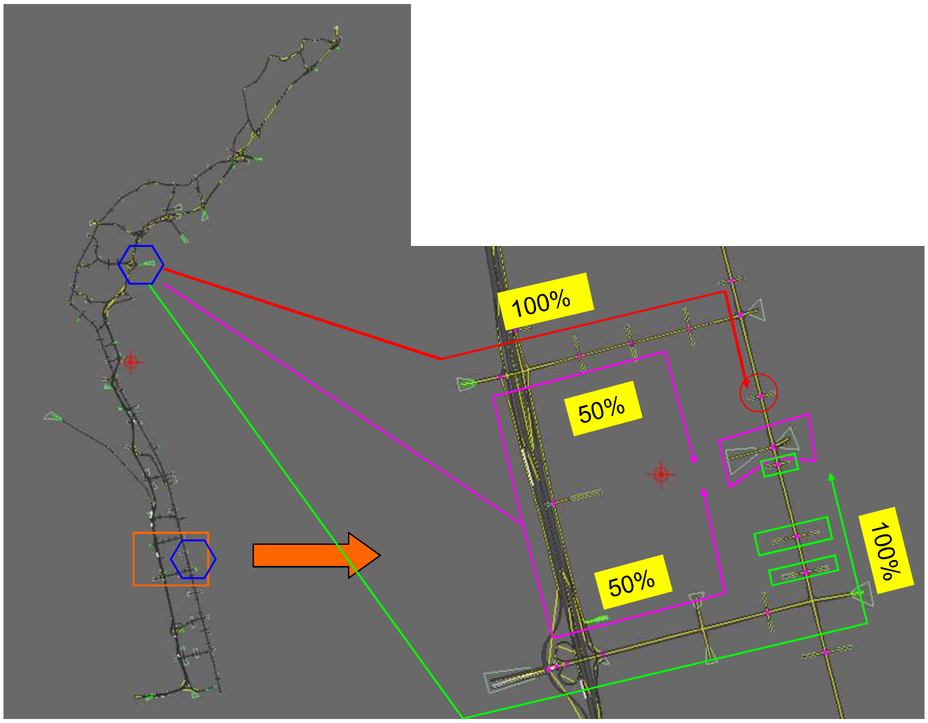

Figure 4.5 The selection of the off-ramp for a vehicle with a destination within the study section

3) If a vehicle has both origin and destination within a distance of less than three major crossroads (not including 3) on San Pablo Ave, it travels on San Pablo Ave and does not use I-80, as shown in Figure 4.6.

Figure 4.6 Short-distance traffic using only San Pablo Ave

By the three rules above, we get the counts of different vehicle type traveling between each pair of origins and destinations from 6 am to 10 am. Then based on the information about the vehicle type (desired speed, maximum acceleration, vehicle length, and so on), we construct the OD matrix for each vehicle type for each one-hour interval and load it into Aimsun.

Recently, data on individual vehicle trajectories were collected and made available under the Next Generation Simulation (NGSIM) project (Alexiadis and Colyar 2004), a national effort aiming to develop improved algorithms and datasets for calibration and validation of traffic simulation models. The NGSIM data provide a unique opportunity to investigate driver behavior, better understand traffic dynamics and formulate improved models.

The NGSIM freeway database consists of vehicle trajectories on two test sites (NGSIM Homepage). The I-80 (BHL) test section is a 0.40 mile (0.64 km) 6-lane freeway weaving section with an HOV lane. Processed data include 45 minutes of vehicle trajectories in transition (4:00-4:15 pm) and congestion (5:00-5:30 pm). The US101 site is a 0.3 mile (0.5 km) weaving section with five lanes. Processed data include 45 minutes of vehicle trajectories in transition (7:50-8:05 am) and congestion (8:05-8:35 am). The data have been extracted from video recordings using machine vision algorithms (Skabardonis and Alexiadis 2005).

Due to its microscopic and ground truth characteristics, NGSIM data is a good data source which can be used to calibrate and validate the microscopic model for saturated traffic such as vehicle following model, lane changing and merging model etc. Since the VSL and CRM to be designed and validated over the microscopic simulation are mainly targeted for saturated/congested traffic, the microscopic model calibrated over NGSIM data could better represent the driver behavior in such a traffic situation. This model has been documented in (Yeo, 2008) and is being used here.

Chapter 4 References:

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Chapter 5 - Combining Variable Speed Limit with Ramp Metering for Freeway Traffic Control

5.1 Introduction

Ramp metering (RM) is the most widely practiced strategy to control freeway traffic. It has gradually been recognized that ramp metering can only directly control one aspect of freeway traffic, the average density immediately downstream of the controlled onramp. Alternatively, ramp metering controls the demand from the onramp into the mainline freeway, but once the drivers get into the freeway, the collective behaviors of the drivers are out of control. This is why using ramp metering alone to control freeway traffic has limited performance if the total demand is high. In addition, from the perspectives of equity among the onramps along a corridor and the ramp queue length limits due to road geometry, ramp metering has to be switched off if the demand from that onramp is too high. Therefore, from a systems and control viewpoint, using ramp metering alone cannot fully control the freeway traffic in practice. This is the motivation for investigating other control strategies.

A directly complementary control strategy at a similar level to RM is *Variable Speed Limits* (VSL), which seeks to control the collective vehicle speed (or driver behavior) of the mainline traffic. Several VSL implementations in Europe (UK, Germany, France and Netherlands) have aimed to harmonize the traffic speed mainly for safety purposes. The evaluations of those strategies did not show significant improvements in mobility although it is generally accepted that accident/incident reductions were between 25~40 percent, a significant improvement. One cannot conclude from those European practices that VSL and RM cannot improve mobility since the VSL control strategies implemented there were either heuristic, not combined with RM, or designed specifically for improving traffic safety rather than traffic flow. To improve mobility using VSL and RM, one has to design the control strategy based on mobility considerations. This does not mean that mobility improvement has to contradict safety improvement. It is quite possible to integrate them both into a single objective function for optimization in control strategy design, which will be an interesting research topic in the future. This chapter will focus on mobility improvement along a stretch of freeway using a combination of VSL and RM.

Theoretical research activities on combined VSL and ramp metering for mobility purposes have been conducted, although few such strategies have actually been implemented. There are several possible ways to combine VSL and RM depending on what model is adopted and how the control strategy is designed, which are classified as the follows:

- RM strategy is determined first (model based approach or non-model based approach), then VSL strategy is determined based on known RM rate and other measured traffic information;
- A tightly combined approach based on tightly coupled second order model involving both density dynamics and speed dynamics; this approach can optimize some objective function such as TTS (Total Time Spent) with the VSL variable and RM rate as the decision parameters;
- Determine VSL first to optimize some objective function, and then determine RM strategy based on known speed limit along the freeway stretch.

It is noted that, for each category, there are many alternatives depending on what models are adopted and how the control strategies for VSL and RM are designed.

The main contribution of this chapter belongs to the first category. Specifically, it assumes that the RM strategy is designed based on the Cell Transmission Model (CTM) of previous work which has been implemented in TOPL (Tools for Operational Planning) (TOPL Project). At each time step, RM control is determined first based on sensor measurement and traffic state parameter estimation; then those parameters and the design metering rate are used as input to a speed dynamics model, which is further used to determine VSL for each section (Cell) of the freeway stretch. The control criterion is to maximize the bottleneck flow to its capacity flow. It is believed that this is a direct approach to reduce TTS.

The traffic problem to be solved is to maximize a recurrent bottleneck flow. The main strategy is to create a free-flow section right above the bottleneck such that the feeding flow into the bottleneck could reach the capacity flow of the bottleneck. This is possible under the assumption that the recurrent bottleneck can be modeled as a lane reduction. This consideration is based on previous works (Banks 1991, Banks 1991, Bertini and Cassidy 2002, Bertini and Leal 2005, Cassidy and Bertini 1999, Hall and Agyemang-Duah 1991, Persaud and Yagar, Zhang and Levinson 2004, Zhang and Levinson 2004) which indicate that congested upstream traffic will reduce the bottleneck flow because the feeding flow will be lower than the capacity flow of the bottleneck. Such a control strategy may not be effective for other types of bottleneck such as those caused by high onramp in-flow, which is naturally accompanied by strong weaving and merging impact. At this stage, we adopt the TOPL as the macro-simulation platform. Since some RM strategies have been implemented in TOPL, we only conduct VSL design based on known RM strategies. This combined control strategy is therefore a loosely coupled RM and VSL. The control design problem focuses on VSL design with RM rate and density as input variables which are determined separately. The control variable or decision parameter is the VSL.

The chapter is organized as follows: Section 5.2 is for literature review of previous work on RM and VSL strategies relevant to this work; Section 5.3 presents higher level control strategy and an approach for combined VSL and RM; Section 5.4 is devoted to *Model Predictive Control* design based on speed dynamics only; Section 5.5 presents macroscopic simulation; and Section 5.6 is for concluding remarks.

5.2 Literature Review

In recent years, model-based traffic control design has been becoming more and more popular. The analysis and control design of ramp metering based on the first order Cell Transmission Model (CTM) is one example (Muñoz and Sun 2004, Gomez and Horowitz 2006)]. Another example is use of a second order model for combined Variable Speed Limit and Coordinated Ramp Meter control design in (Papageorgiou 1983, Papageorgiou and Blosseville 1990, Papamichail and Kampitaki 2008, Hegyi and Schutter 2005). This chapter addresses some modelling issues based on practical traffic control design considerations.

5.2.1 Ramp Metering

RM Algorithms

For a good review of freeway ramp metering approaches see (Papageorgiou and Kotsialos 2002). Coordinated ramp metering used a second order model, although speed is not controlled. Other effects including merging and weaving were also considered. The ramp metering methods are mainly two: ALINEA, and Coordinated RM, with extension over traffic networks. Several RM strategies were also reviewed and compared in (Zhang and Kim 2001).

ALINEA, a local traffic responsive RM, is getting more and more popular in practice. (Scariza 2003) evaluated four ramp metering methods: ALINEA-local traffic responsive; ALKINEA/Q based ALINEA with onramp queue handling; and FLOW - a coordinated algorithm that tries to keep the traffic at a predefined bottleneck below capacity; and the Linked Algorithm is a coordinated algorithm that seeks to optimize a linear-quadratic objective function. The most significant result was that ramp metering, especially the coordinated algorithms, was only effective when the ramps are spaced closely together.

System Wide Adaptive Ramp Metering (SWARM) is a relatively new ramp meter operating system developed by National Engineering Technology (NET) Corporation, based on Caltrans District 7's, ramp metering unit inputs and recommendations. SWARM is not model based, but is totally based on measurement of linear regression for prediction of density. A good review and implementation of SWARM is documented in (Caltrans District 7 2005-2006).

Ramp Metering Advantages

Ramp metering has many potential advantages (Roess and McShane 1998):

- Access control and traffic diverting to other, less congested roads ➔ Improvement of freeway mainline flow
- Metering smoothes out the traffic flow and breaks up platoons ➔ allowing more efficient merging, and reduction of crashes, fuel consumption, emissions, and vehicle operating costs
- Network routings may be altered to achieve greater balance and efficiency.

Ramp Metering Disadvantages

- can lead to long queues on the ramps, and lead to delays for on-ramp traffic.
- network rerouting can possibly have negative effects on alternate routes
- ramp traffic can back up onto surface streets
- ramp meters make it difficult to accelerate to high speed on the ramp, so ramp meters
  - cause problems for merging
  - should only be used when highway speed is fairly low
- Need to take into account freeway configuration

Since the density directly affects the traffic flow, even a local high density could cause a moving jam – propagating forward, backward, or in both directions (Cassidy and Bertini 1999), it is necessary to investigate the density distribution for ramp meter injection: in lower density permit more traffic injection and in high density permit less or no traffic injection. It is not appropriate to just control the average density since inputting a vehicle stream from an onramp into a high density stream might cause a wide moving jam or bottleneck.

5.2.2 Simulation of RM in TOPL

The goal of ramp metering control is to manage the on-ramp flow so as to increase the mainline flow on the freeway. The controller determines the maximum flow which an on-ramp can release into the freeway. If no controller is assigned to an on-ramp, its flow is restricted by the ramp capacity and available capacity of the cell to which this on-ramp belongs. CTMSIM (Kurzhanskiy 2007), as part of the TOPL macroscopic traffic simulation package (TOPL Project), provides several on-ramp metering control options, and the implemented algorithms include Asservissement Linéaire d'Entrée Autoroutière (ALINEA), Linear Quadratic Control with Integral action (LQI), System-Wide Adaptive Ramp Metering (SWARM) and the so-called ideal ramp metering (IRM) strategy. ALINEA was the first local ramp-metering control strategy to be based on straightforward application of classical feedback control theory, and has been widely deployed in European countries (Papageorgiou and Hadl-Salem 1997). The ALINEA controller is adopted in this study.

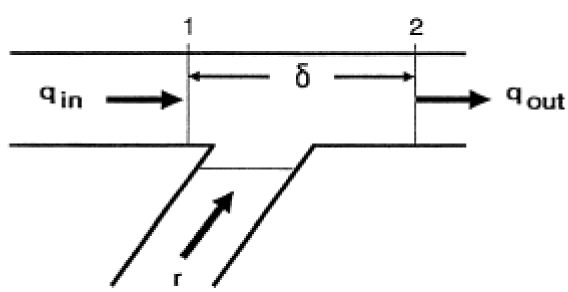

Figure 5.1 Variables for local ramp metering control [PAPAG_0]

ALINEA considers traffic flow as the process being controlled and the metering rate as the control variable. Based on feedback control theory, the algorithm attempts to set the metering rate such that traffic flow will not exceed system capacity. For each time interval, the algorithm solves the following equation for metering rates at each on-ramp:

$$r(k) = r(k-1) + K\left[\rho_c - \rho(k)\right] \tag{5.1}$$

where:

$r(k)$: on-ramp metering rate (vph) in time interval k

$K > 0$: pre-calibrated control gain, which may be different from link to link

$\rho_{out}(k)$: local density downstream of on-ramp entrance (Figure 5.1)

ρ_c: critical density downstream of on-ramp entrance

The ALINEA algorithm (5.1) is simply a proportional controller without any model. It requires one mainline detector station downstream of the on-ramp entrance. The detector should be able to capture the congestion originating from excessive on-ramp flows. Measurement of $r(k)$ may also be necessary.

5.2.3 VSL Strategies

Corridor Range Coordinated VSL

Freeway congestion can be classified in two types according to causes (Juan and Zhang 2004): (a) demand driven - due to the increase of traffic volume; and (b) supply driven - due to the road geometric condition, weather or traffic incident. Simulation has been focused on the cause of congestion. Several factors have been considered, which lead to the instability of freeway traffic flow including small headway, large speed variance and frequent disturbances. Many scenarios of VSL have been simulated.

Work in (Lin and Kang 2004) presents two VSL algorithms for traffic improvement, which did not consider the combination with ramp metering. The author believes that VSL not only can improve safety and emissions, but also can improve traffic performance by increasing throughput and reducing time delay. The methods were primarily proposed for work zones, however, since work zones are a typical bottleneck with lane reduction frequently known in advance, this method can be generalized for application to some other bottlenecks. The first method is for reducing time delay by minimizing the queue upstream of the work zone; the second method is for reducing Total Time Spent (TTS) by maximizing throughput over the entire work zone area. Simulation results showed that the first method may even outperform the second method on speed variance reduction despite there being no optimization involved.

Network Range Coordinated VSL

Because traffic at one point in the network would affect other parts of the network, it is necessary to consider traffic control in the network instead of locally. Two distinct functions of VSL are speed homogenization and prevention of traffic breakdown. Speed homogenization reduces speed variance; its effect on traffic mobility is negligible (van der Hoogen and Smulders 1994) although it has a positive effect on safety. Prevention of traffic breakdown avoids high density, achieving density distribution control through VSL. As an example, Hegyi at al (Hegyi and Schutter 2005) use VSL strategy to suppress shock waves.

(Wang and Wang 2007) considered speed dispersion (fluctuation w. r. t. mean speed) for freeway traffic flow. The results claimed to support microscopic traffic modeling. It considered the relationship among speed, flow and density in the Fundamental Diagram (FD) for steady state. It is a hypothetical solution for the traffic flow theory. However, this paper claims that such a FD cannot be observed in real traffic conditions.

Experimental Work on VSL

Preliminary Variable Speed Limit (VSL) strategies have been used in Germany (Bertini and Boice 2007, Robinson 2000). The research in (Bertini and Boice 2007) used an empirical approach to investigate the effectiveness of reducing congestion at a recurrent bottleneck and to improve driver safety by using feedback to the driver with advisory Variable Message Sign (VMS) at certain locations along a stretch of highway (18 km). The feedback includes (a) speed limit (piecewise constant with 12 km/h increment) and start/end time/location; and (b) warning information (attention, congestion, slippery). The suggested speed was based on the traffic situation upstream and downstream of the bottleneck. Data analysis showed that driver response to the speed limit and messages on the VMS was reasonable, speed was regulated to some extent, and improvement in safety was more significant than on traffic, up to 20%~30%.

The Dutch experiment (van der Hoogan and Smulders 1994) intended to smooth or homogenize the traffic flow along a stretch of highway by VSL. A speed limit was enforced when volume approached the capacity, and kept constant along a section of the freeway. Only two speed limits, i.e. 70 km/h and 90 km/h were used, with an update rate of one minute. Real-time measurements were the traffic volume and average traffic speed in each section. Tests were conducted on multiple stretches totaling 200 km in the Netherlands. Work showed that speed control was effective to some extent in reducing speed and speed-variation, as well as the number of shockwaves. Moreover, it was particularly effective on the portions of freeway where vehicles maintained a small driving headway. However, no significantly positive effect on capacity, flow and volume was observed (van der Hoogan and Smulders 1994). Besides, the overall performance of the freeway was not significantly enhanced. This may suggest that it is necessary to combine VSL with other methods, such as RM.

Several empirical VSL studies have been conducted in the U.S. since the 1960s in several states with varying levels of development for different purposes (to improve traffic safety, work-zone safety, or traffic flow) (Warren 2003). The outcomes were diverse, with some positive and most negative. The most impressive positive outcome was the work conducted by the state of New Jersey, which was similar to the approach in Germany, but with the speed enforced instead of advised. Some experiments on individual vehicle speed advisory/enforcement have also been successfully conducted for trucks downhill. Preliminary micro-simulation work combining ramp metering with VSL was reported in (Abdel-Aty and Dhindsa 2007). The model and ramp metering strategy adopted there were rather simple and might not reflect the true corridor traffic dynamics and driver behavior, and might not be able to handle significant traffic uncertainties.

Evaluation of VSL Effect on Mobility

Papageorgiou (Papageorgiou and Kosmatopoulos 2008) evaluated some implemented VSL strategies based on data analysis. The paper summarizes available information on the VSL impact on Fundamental Diagram-aggregate traffic flow behavior. The observed effects included:

- decrease the slope of the flow-occupancy diagram at under-critical conditions;
- shift the critical occupancy to higher values;
- enable higher flows at the same occupancy values in overcritical conditions.

It concluded that there was no clear evidence of improved traffic flow efficiency in operational VSL systems for the implemented VSL strategies.

<u>*5.2.4 Combined VSL and RM*</u>

Abdel-Aty considered both Variable Speed Limits and Ramp Metering, which are believed to be the two key tools that can help in influencing conditions on congested freeways. Using micro-simulation, this paper showed the positive effects of the individual strategies. Their combined effect was also studied in reducing the risk of crash and improvement in operational parameters such as speeds and travel times. (Caligaris and Sacone 2007, Allisandri and Di Febbraro 1998) used a second order model for optimal control of both speed and ramp metering: speed control and density control. This is a well-written paper: clear concept, mathematically correct, rational from traffic viewpoint, system isolation and modeling is clear, and state variable choice is reasonable. (Hegyi and Schutter 2005) considered optimal combined speed limit and ramp metering based on the METANET model using model predictive control.

Papamichail considered combined VLS and coordinated ramp metering with an optimal control approach. It was formulated as a Model Predictive Control (MPC) problem with the second order METANET model; it presented an algorithm feasible for large scale systems; it showed by simulation that traffic flow significantly improved with combined VSL and Ramp Metering compared to RM or VSL alone.

(Hegyi and Schutter 2002) considered combined ramp metering and VSL, particularly how the combination would work, based on the Fundamental Diagram. The authors believed that ramp metering is useful only when the traffic demand is not too high. Otherwise, it will break down and ramp metering has no use. The basic idea of the paper is that when density is high, the following chain effect would result: Coordinated VSL upstream ➔ Reduce density downstream ➔ changing the shape of the fundamental Diagram ➔ allowing more vehicles in from onramp ➔ preventing breakdown if no demand from on-ramp ; or postponing traffic breakdown if there is a large demand from on-ramp ➔ increase the effective range of ramp metering. This is due to the capacity drop phenomenon when upstream traffic is congested: the out-flow is lower than in the non-congested situation for the same bottleneck. Just because of this, the VSL could reduce TTS (Total Time Spent).

5.3 Joint VSL and RM Design

This section presents the main new results of this chapter, i.e. design of VSL based on known RM strategy for a stretch of freeway as shown in Figure 5.2. The objective is to maximize the recurrent bottleneck flow to its capacity flow. The definition of "Cell" is referred to [yyyDaganzo]. The following notations are used in the discussion:

$m-$ link index; each link has exactly one onramp; it may have no or more than one off-ramps
n_m- the number of cells in link m; each cell contains exactly one traffic detector
$M-$ number of links concerned - the length of the influence zone upstream of the bottleneck; link M is the first link immediately upstream of the discharge section;
$i-$ cell index (a link may be divided into several cells)
$k-$ real-time evolving index
$r_m(k)-$ onramp metering flow rate (veh/hr)- control variable
$s_m(k)-$ total off-ramp flow rate (veh/hr); assumed to be measured and thus known to time k
$N-$ time step for control simulation

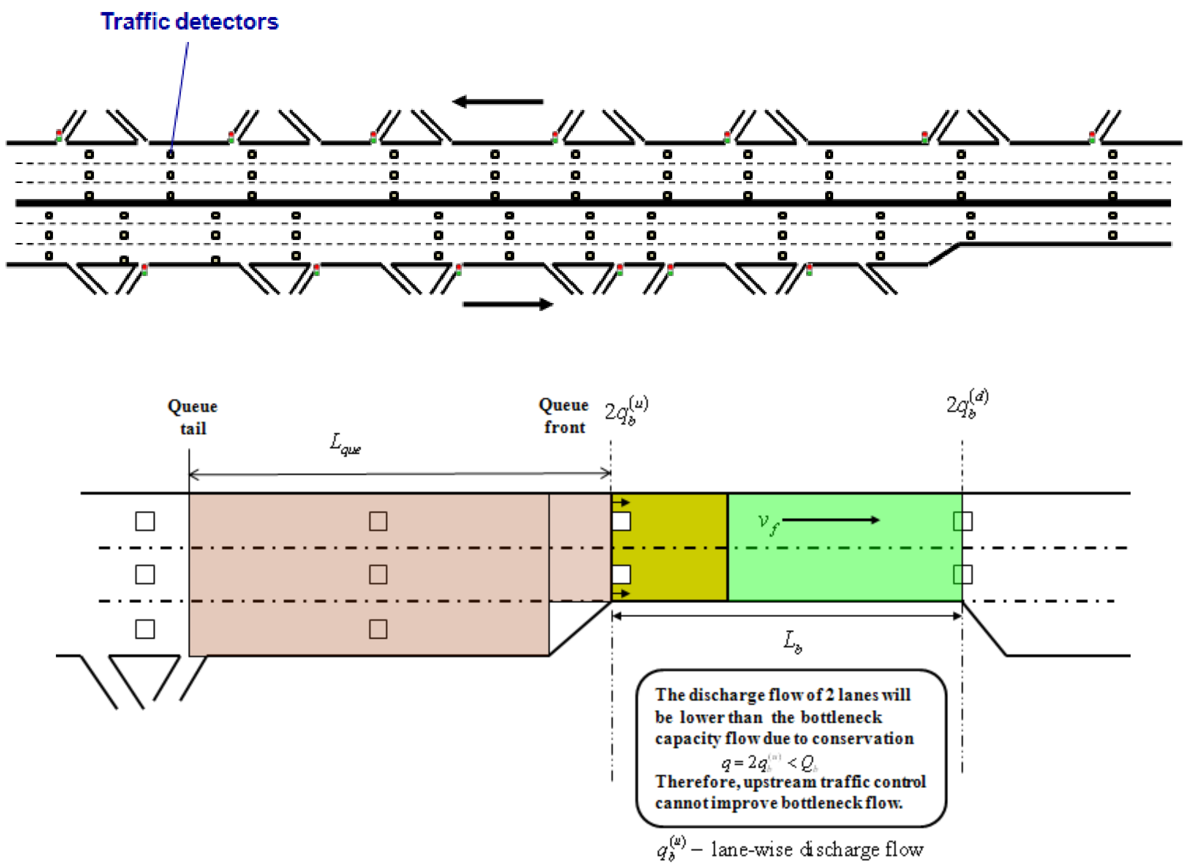

Figure 5.2 Upper: A stretch of freeway with recurrent bottleneck that can be modeled as a lane drop; Lower: the bottleneck, where the discharge flow of two lanes will be lower than the bottleneck capacity flow due to conservation $q = 2q_b^{(u)} < Q_b$; $q_b^{(u)}$ is lane-wise discharge flow.

Recurrent Bottleneck Traffic Characteristics

This analysis applies to a recurrent bottleneck that can be modeled as a lane reduction, such as a work-zone lane closure, geometric design, freeway split, etc. To understand bottleneck flow characteristics, the following concepts are crucial:

Bottleneck Capacity: Physical capacity of the bottleneck or its maximum flow;

Bottleneck Discharge flow: The following cases are not distinguished: (a) upstream cell is congested with queue but there is no queue within the bottleneck; and (b) both cells and part of the bottleneck stretch are congested with queue.

Bottleneck feeding flow: the flow at the starting point (mouth) of the bottleneck.

As the results of field data analysis from (Banks 1991, Banks 1991, Bertini and Boice 2006, Bertini and Cassidy 2002, Cassidy and Bertini 1999, Hall 1991, Persaud and Yagar, Zhang and Levinson 2004, Zhang and Levinson 2004 show, congested upstream traffic will reduce the bottleneck flow. Essentially, this is due to lower feeding flow to the bottleneck.

Control Strategy

Based on the traffic characteristics, the following control strategy is proposed for the following situation: if the demand is too high from both upstream and onramp and congestion is unavoidable, then create a free-flow section right above the bottleneck by defining a critical VSL as shown in Figure 2 such that the feeding flow to the bottleneck is approximately the capacity flow of the bottleneck. This is possible if there is a lane drop right upstream of the bottleneck. It can be proved that maximizing the bottleneck flow is equivalent to reducing the TTS under the assumption that all the traffic has to pass the bottleneck.

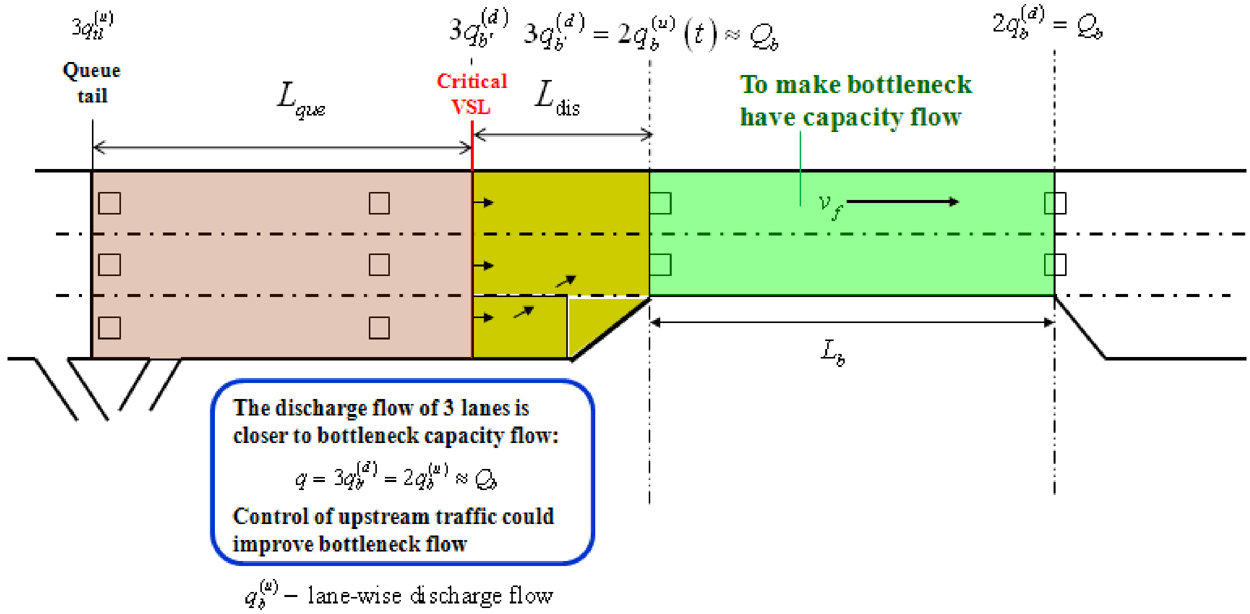

Figure 5.3 Control strategy: to maximize bottleneck flow; the discharge flow of 3 lanes is closer to bottleneck capacity flow: $q = 3q_{b'}^{(d)} = 2q_b^{(u)} \approx Q_b$; Control of upstream traffic could improve bottleneck flow

Control Problem Formulation

After applying the control at time step *k*, we are going to design the control for time step *k+1*, the control parameters are to be determined over the *predictive time horizon* $\left[k+1, k+2, \ldots, k+N_p\right]$ with MPC control procedure as the decision parameters:

$$\mathbf{u} = \left[u_1(k+1), \ldots, u_1(k+N_p), \ldots, u_m(k+1), \ldots, u_m(k+N_p), \ldots, u_M(k+1), \ldots, u_M(k+N_p)\right]^T \tag{5.2}$$

It is assumed that the RM rate is determined at each time step by a different mechanism.

Control Strategy

Modeling

The model necessary for VSL control design must include speed dynamics. Based on our analysis of the second order model, we select the following speed dynamics model for this purpose:

$$\rho_{m,i}(k+1)=\rho_{m,i}(k)+\frac{T}{L_{m,i}\lambda_{m,i}}\left(\rho_{m,i-1}(k)v_{m,i-1}(k)-\rho_{m,i}(k)v_{m,i}(k)+r_i(k)-s_i(k)\right)$$

$$v_{m,i}(k+1)=v_{m,i}(k)+\frac{T}{\tau}\left(u_{m,i}(k)-v_{m,i}(k)\right)+\frac{T}{L_{m,i}}v_{m,i}(k)\left(v_{m,i-1}(k)-v_{m,i}(k)\right)-$$
$$\frac{1}{\tau}\left(\frac{\nu T}{L_{m,i}}\frac{\rho_{m,i+1}(k)-\rho_{m,i}(k)}{\rho_{m,i}(k)+\kappa}\right) \tag{5.3}$$

$$u_{m,i}(k)=u_m(k),\quad i=0,1,\ldots,n_m;m=1,\ldots,M$$

This is a simplified METANET model with two major modifications: (a) there is no further parameterization in the speed control variable $u_{m,i}(k)$; (b) there is no assumption of the FD. The advantages of doing so include:

- Speed control variable appears linearly;
- Two degrees of freedom for control design: both VSL and RM rate;
- Effectively avoiding model mismatch caused by the discrepancy of field data and the FD curve;
- Proper constraints will be added to the optimization problem from an empirical traffic flow drop probability analysis with respect to both speed and density (occupancy) [32].

Here it is assumed that at each time step k, the RM rate

$$\hat{\mathbf{r}}=\left[r_1(k+1),\ldots,r_1(k+N_p),\ldots,r_m(k+1),\ldots,r_m(k+N_p),\ldots,r_M(k+1),\ldots,r_M(k+N_p)\right]^T \tag{5.4}$$

is independently determined by an RM strategy over the time horizon, which is necessary for the prediction over the same time horizon using the model above.

Constraints

For given Preferred Reference Density (PRD) (determined by RM strategy), the Preferred Reference Speed (PRS) is determined at the potential queue front (the Critical VSL control point) by:

$$\begin{gathered}\lambda_M\rho_M(k+j+1)v_M(k+j+1)=Q_b\\ j=1,\ldots,N_p\end{gathered} \tag{5.5}$$

which is further relaxed as an inequality constraint:

$$\begin{gathered}Q_b-\varepsilon\le\lambda_M\rho_M(k+j+1)v_M(k+j+1)\le Q_b+\varepsilon\\ 0<\varepsilon \text{ is a small number.}\end{gathered} \tag{5.6}$$

which is an implicit constraint on the control variable. Therefore it needs converting to direct constraints by the system dynamics (3.2). Denote

$$\mathbf{u}_M = \left[\bar{u}_M\left(k+1\right),...,\bar{u}_M\left(k+N_p\right)\right]^T \tag{5.7}$$

which are the critical VSL and can be calculated based on the RM rate from ALINEA. Based on consideration of safety, driver acceptance and traffic flow characteristics, the following constraints on the VSL control variable are adopted:

$$\begin{aligned} &0 \le u_m\left(k\right) \le \bar{V}_m \\ &-5 \le u_m\left(k-1\right) - u_m\left(k\right) \le 5 \end{aligned} \tag{5.8}$$

The first one is the bounds for the VSL and the second is the speed increment/decrement limit over time.

The following inequality limits the feasible region in the speed and density plane:

$$v_m + a\rho^2{}_m\left(k\right) + b\rho_m\left(k\right) \le \eta_m \tag{5.9}$$

where η_m is a design parameter to be tuned off-line. This constraint is from the following consideration: density and speed are upper bounded by a contour on the speed-density plane.

The boundary of the strip is the contour of traffic drop probability in the speed-density plane (Chow and Lu). The constraints provide more flexibility for the control system compared to the strict constraint on the FD curve adopted in the METANET model (Papageorgiou 1983, Papamichail and Kampitaki 2008, Hegyi and Schutter 2005). This is a significant difference compared to other work using the METANET model.

Objective Function

The following objective function is used over the predictive time horizon:

$$J = T\sum_{j=1}^{N_p}\sum_{m=1}^{M} L_m\lambda_m\left[\alpha_{TTT}\rho_m\left(k+j\right) - \alpha_{TTD}v_m(k+j)\cdot\rho_m\left(k+j\right)\right] \tag{5.10}$$

The first term is TTT (Total Travel Time); the second term maximizes the TTD (Total Travel Distance). The parameters $\left(\alpha_{TTT},\alpha_{TTD}\right)$ are selected at the simulation stage.

About Discharge Section Length Determination

The length of L_{dis} in Figure 5.3 is determined by the distance requirement for the vehicle to accelerate from zero speed (the worst case) to the desired speed, which can be determined from the designed speed limit at the bottleneck.

$$L_{dis} = \frac{V_{tgt}^2}{2a_{ave}} + 200 \tag{5.11}$$

$a_{ave} -$ average acceleration
$V_{tgt} -$ desired speed at the bottleneck.

The added 200 m takes into account other important factors such as weaving and lane changing effects, which may be tuned slightly in the implementation.

As an example, for the passenger car, suppose the average acceleration capability is 1.5 m/s^2. . If the speed allowed at the bottleneck is 65 mph (~29.1 m/s), then the distance required for the vehicle to accelerate from 0 to 29.1 m/s is about

$$L_{dis} = \frac{29.1^2}{2 \times 1.5} + 200 \approx 500[m]$$

5.4 Model Predictive Control (MPC) Control Design for VSL

Because the control design in TOPL predicts only one step ahead, MPC design is used here. For any given time starting from *k*, the control parameters are to be determined in the MPC procedure as the decision parameters for time *k+1*:

$$\mathbf{u} = \left[u_1(k+1),...,u_1(k+N_p),...,u_m(k+1),...,u_m(k+N_p),...,u_M(k+1),...,u_M(k+N_p)\right]^T$$

The optimal solution is denoted as

$$\overline{\mathbf{u}} = \left[\overline{u}_1(k+1),...,\overline{u}_1(k+N_p),...,\overline{u}_m(k+1),...,\overline{u}_m(k+N_p),...,\overline{u}_M(k+1),...,\overline{u}_M(k+N_p)\right]^T$$

The predicted traffic state parameters for the next time step are:

$$\hat{\mathbf{v}} = \left[\hat{v}_1(k+1),...,\hat{v}_1(k+N_p),...,\hat{v}_m(k+1),...,\hat{v}_m(k+N_p),...,\hat{v}_M(k+1),...,\hat{v}_M(k+N_p)\right]^T$$
$$\hat{\boldsymbol{\rho}} = \left[\hat{\rho}_1(k+1),...,\hat{\rho}_1(k+N_p),...,\hat{\rho}_m(k+1),...,\hat{\rho}_m(k+N_p),...,\hat{\rho}_M(k+1),...,\hat{\rho}_M(k+N_p)\right]$$

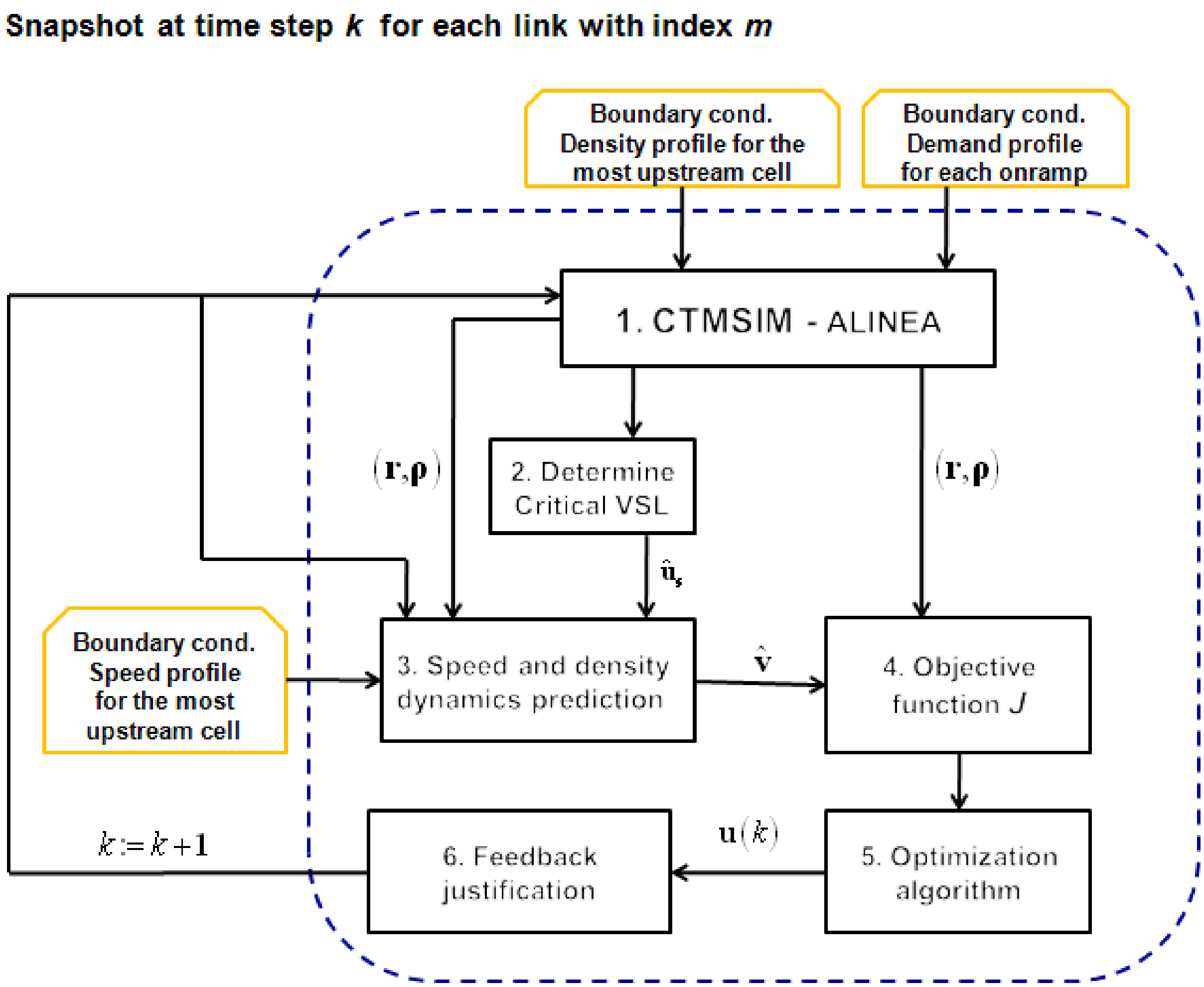

Figure 5.4 MPC mechanism to determine VSL over the time horizon

The MPC mechanism works in the following logical order for each time step *k*, as shown in Figure 5.4:

(1). CTMSIM determines RM rate for each on ramp and density for each cell;
(2). Critical density is determined over the predictive time horizon from (5.6);
(3). Modified METANET model (5.3) is used for speed and density prediction over the predictive time horizon;
(4). Objective function is evaluated;
(5). Optimization algorithm is applied to obtain the desired VSL over the time horizon;
(6). The output is modified to adapt to driver behavior and then displayed.
(7). Set $k := k + 1$ and go to Step 1.

5.5 Sequential Quadratic Programming (SQP) Optimization Approach

Sequential quadratic programming (SQP) methods attempt to solve a nonlinear program directly rather than convert it to a sequence of unconstrained minimization problems (Bonnans, 2006). The basic idea is analogous to Newton's method for unconstrained minimization: at each step, a local model of the optimization problem is constructed and solved, yielding a step (hopefully) toward the solution of the original problem. In unconstrained minimization, only the objective function must be approximated, and the local model is quadratic. In the NLP

$$\min f(\mathbf{x})$$
$$\mathbf{l} \le c_i(\mathbf{x}) \le \mathbf{u}$$
$$c_e(\mathbf{x}) = \mathbf{0}$$

both the objective function and the constraint must be modeled. An SQP method uses a quadratic model for the objective function and a linear model of the constraint. A nonlinear program in which the objective function is quadratic and the constraints are linear is called a quadratic program (QP). An SQP method solves a QP at each iteration.

The software package SQPlab stands for Sequential Quadratic Programming (SQP) laboratory, and is written in Matlab and is used by the author (Gilbert, 2009) as a kind of laboratory for trying techniques related to the SQP algorithm, but it has been designed so that it can be useful to many aspects. SQPlab is adopted as the solution tool to determine optimal control parameters for each time step in this study.

5.6 Simulation Results

To validate the proposed method, the control algorithm described above has been implemented and the practical data from the Berkeley Highway Laboratory (BHL) system have been used. BHL is a test site that covers 2.7 miles of I-80 eastbound immediately east of the San Francisco-Oakland Bay Bridge in California, which can be seen in Figure 5.5. Each detector station is dual loop, providing 60 Hz event data on individual vehicle actuations. Based on the raw BHL event data, accurate aggregated flow and speed information can be extracted. The model parameters are chosen to minimize the quadratic errors between the model computed and the actually measured values of speed and flows. After the calibration procedure, the following parameter values are adopted in the proposed modified METANET model: $\tau = 0.02$, $\nu = 8.5$, $\kappa = 32$; $\alpha_{TTT} = 55, \alpha_{TTD} = 1.$ are used in the proposed objective function for optimizing.

The suggested two locations for VSL signs are between Stations 1 and 2 and between Stations 5 and 6 in Figure 5.5. The simulation starting time is 2:00 pm on December 1, 2005, corresponding to the time index 0 on the X axis, and the ending time of simulation is 12:00 am on December 2, 2005, associated with the time index 600. >From Figure 5.6 it should be noted that VSL control sometimes slows down the traffic flow, for example before the time index 60 (3:00 pm), but on average its effects make a performance improvement with all the cost function components. The initial conditions of simulation are the same for both controlled and uncontrolled cases, coming directly from the measured BHL data. The proposed control strategy is particularly effective against congestion. The VSL improved traffic stability, with more constant flow and a higher average speed as can be seen from Figures 5.6 and 5.7, comparing the traffic with and without VSL for the peak hours from 3:00 pm to 7:00 pm, for Station 2 and Station 6 respectively.

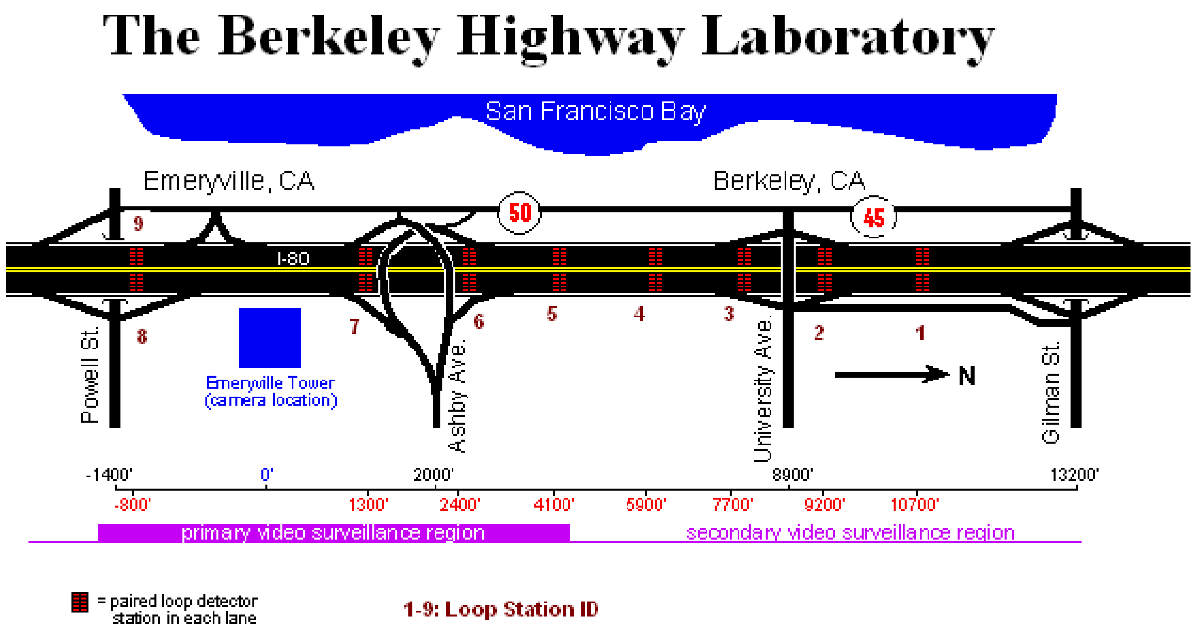

Figure 5.5 Studied freeway stretch – BHL covered area

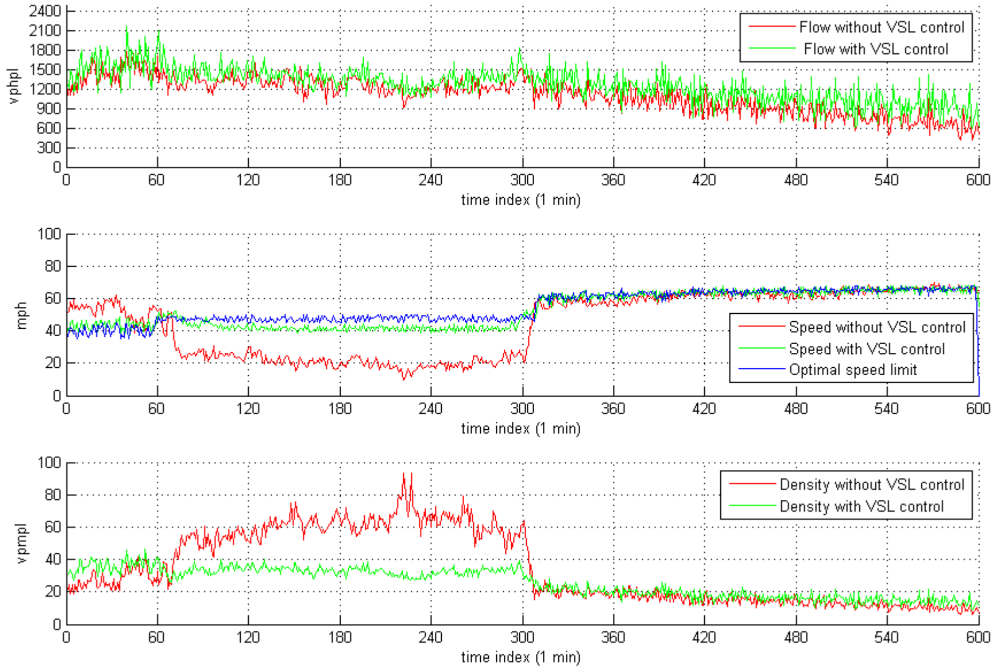

Figure 5.6 Performance Comparison: with and without VSL at Station 2

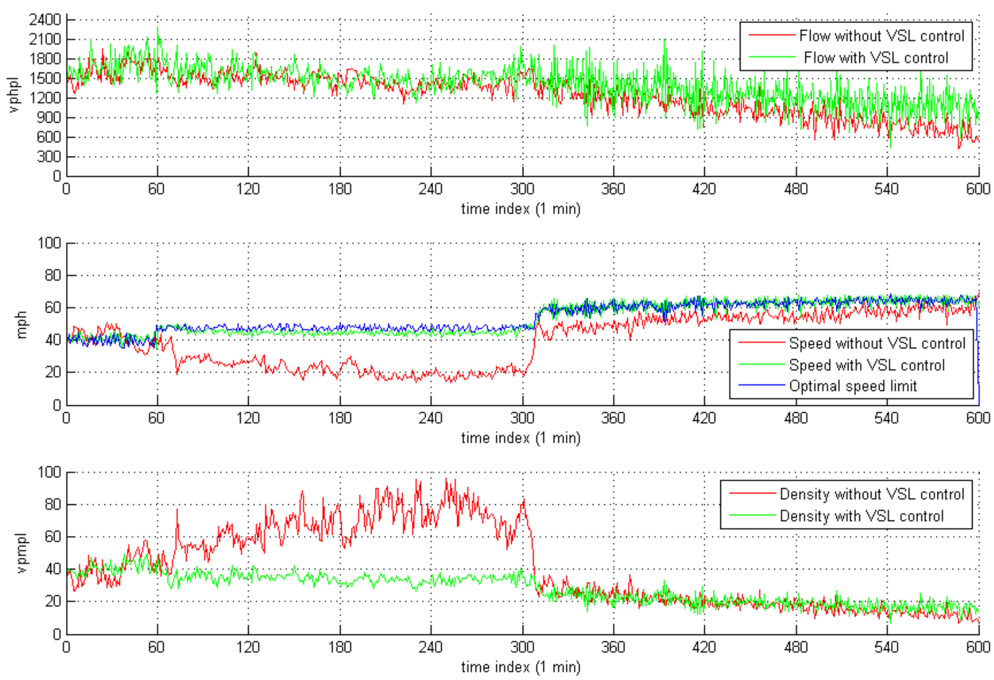

Figure 5.7 Performance Comparison: with and without VSL at Station 6

The following are the accumulated performance parameters over the ten hour simulation period and five lanes, showing the improvements using VSL (Table 5.1). The data have been averaged over several simulation runs.

Table 5.1: **Performance Comparison**

Performance	Without	With VSL
TTT (hrs)	5150	3510
TTD (miles)	157385	177645
Flow (vphpl)	314775	355290
Obj. Function	125865	15405

5.7 Concluding Remarks

The METANET model has been simplified by dropping the assumption of the fundamental diagram and the re-parameterization of the speed control variable. With the simplified METANET model representing speed and density dynamics and under the assumption that the RM rate is determined by a separate approach, VSL control has been designed using Finite Time Horizon MPC. Simulation has been conducted over the I-80 BHL section, showing that VSL improves traffic noticeably.

This algorithm could be used in cases where RM or CRM has been implemented successfully. It does not depend on the RM algorithm, but its eventual performance will be affected by the RM or CRM performance. This is essentially a decoupled approach and is simpler than a tightly coupled approach. The advantage of this approach is full use of the implemented RM or CRM facilities. The disadvantage is that such a decoupled approach may be able to achieve system optimum in theory, but not necessarily in practice since the traffic system has significant uncertainties – the simpler approach may have comparable performance to a very complicated approach. In future work, it would be interesting to compare different approaches for the combination of VSL and CRM for different traffic situations. It is noted that the one designed first would have higher priority in the control process in principle. For example, the following combinations are worth testing:

- Design different types of CRM first based on a first order model, and then design VSL based on the second order model above;
- Design VSL strategy first based on second order model, and then design VSL on top of that;
- Design VSL and CRM based on the simplified METANET model at the same time (tightly coupled);
- Apply those controllers to different traffic situations.

From a traffic control system viewpoint, the performance of the controller mainly depends on the following factors: (a) faithfulness of the model (or model mismatch) including internal uncertainties such as driver behavior; (b) external uncertainty; (c) data quality (time delay, measurement noise, and estimation error); and (d) how the control is implemented. As an example, since the ramp meter rate directly affect the of immediate average density downstream of the meter, which in turn directly affects the traffic flow, even a local high density could cause a moving jam – propagating forward, backward, or in both directions (Cassidy and Bertini 1999). For RM or CRM to have good performance, it is necessary to investigate the density distribution for ramp meter injection: where there is lower density with more traffic injection and where there is high density with less or no traffic injection. Likewise, how to implement the VSL feedback to the driver to achieve the best driver response with minimum time delay and variance needs further consideration.

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Chapter 6. Estimation of Traffic Breakdown Probability

6.1. Introduction

This chapter investigates the stochastic nature of traffic breakdown for control purposes. From the operations point of view, traffic breakdown is usually defined as when average speed of traffic drops rapidly below a certain threshold (Banks, 2006). It is widely believed that breakdown occurs when the flow rate of traffic passing through a bottleneck exceeds its capacity. The Highway Capacity Manual (HCM) defines the capacity of a bottleneck as the maximum sustainable flow at which vehicles and persons reasonably can be expected to traverse it during a specified time period under given roadway, geometric, traffic, environment, and control conditions (Transportation Research Board, 2000). Further details of the HCM approach can be found in Section 1.2 in Banks (2006). HCM considers the highway capacity and the associated traffic breakdown to be deterministic in nature. However, it has been revealed that breakdown occurrences are indeed stochastic, which can happen even when the traffic flow is below the capacity (Elefteriadou et al., 1995). Evans et al. (2001) first developed a model to estimate the probability of breakdown at ramps by using Markov chains. Lorenz and Elefteriadou (2001) performed an empirical analysis of speed and flow data collected from Highway 401 in Toronto, Canada. Based on empirical observations, Lorenz and Elefteriadou (2001) defined that breakdown occurs when the average speed of traffic on all lanes drops below 90 km/h (~56 mph) for a period of at least five minutes.

Recently, Brilon et al. (2005) proposed an empirical approach to analyze the probability of breakdown based on a univariate Weibull distribution with respect to flow. They looked at the traffic data collected from freeways A1 and A3 in Cologne, Germany. The data included flow rates and speeds, which were aggregated into 5-min intervals. The size of the time interval (5 min) was selected after a series of experiments (Brilon and Zurlinden, 2003). Nevertheless, it is known that a particular flow can represent two different traffic states: uncongested and congested. Uncongested state corresponds to traffic with a high speed (so-called free-flow speed, ~60 mph) but a low density (below critical density, around 30 vehicles per mile per lane (vpmpl)); congested state represents traffic with a low speed (below 45 mph) but a high density (above critical density). Thus, simply considering flow is inadequate for traffic control. Moreover, Brilon et al. (2005) adopted a binary classification to divide traffic into either uncongested or congested based on a predefined speed threshold. Traffic breakdown is regarded as the transition from uncongested traffic to congestion. With Brilon's definition, a breakdown is only counted when the mean speed of approaching traffic is above the speed threshold, which was set to be 45 mph by Brilon et al. (2005). As a result, breakdown events can only be observed on the left limb (uncongested part) of the Fundamental Diagram but none on the right limb (congested part). This gave us no information on the further transition from congested flow to standstill (speed < 30 mph). Indeed, understanding the transition from moderate congestion to complete standstill is important for implementing traffic control (see Kerner, 2004; Lu et al., 2009). Under some scenarios (e.g. morning and evening peaks), traffic demand is so heavy that it is just impossible to retain free flow however traffic is controlled. As our ultimate goal is to derive traffic control strategies that can function under a wide range of scenarios rather than simply under uncongested state, we need to have a better definition of breakdown to capture the entire flow-density diagram.

This study first extends Brilon's (2005) univariate approach to bivariate in terms of mathematical formulation. The probability of traffic breakdown is represented as a function of both average speed and density of incoming traffic. In addition to Brilon's binary classification of traffic, this study analyzes three alternative definitions of traffic breakdown and selects the most suitable one for traffic control purposes. A case study is performed on a section of the I-80 freeway in the San Francisco Bay Area using Berkeley Highway Laboratory (BHL) data. The Berkeley Highway Laboratory (BHL) data were collected from a 2.7 mile section of Interstate 80 in west Berkeley and Emeryville. The BHL facility consists of eight video cameras and sixteen directional dual-inductive-loop-detector stations to monitor I-80 traffic. The outcome of this study is expected to be used for developing active traffic control strategies including variable speed limits and ramp metering.

This chapter is organized as follows: Section 6.2 starts with an introduction to the BHL test site. Section 6.3 discusses four different definitions of traffic flow breakdown for traffic control purposes. The breakdown definitions are analyzed with BHL data. Section 6.4 discusses the application to variable speed limit and ramp metering control. Finally, Section 6.5 gives a conclusion.

6.2. BHL test site

The Berkeley Highway Laboratory (BHL) project (see BHL, 2009) is sponsored by the California Department of Transportation (Caltrans). The BHL facility, as shown in Figure 6.1, consists of eight cameras and sixteen directional dual-inductive-loop-detector stations on a 2.7 mile section of I-80 in the San Francisco Bay Area, from Powell Street in Emeryville to Gilman Street in Berkeley. In the figure, Point A is the location of Station 1; Point B is the location of Station 2, and so on. Eastbound traffic (i.e., I-80E) flows from Station 8 to Station 1 (from H to A), while I-80W traffic flows from Station 1 to Station 8 (from A to H). Traffic data (flow, occupancy, and speed) are collected at 60 Hz.

In our study, traffic data were collected on the weekdays from 21 November 2005 to 16 December 2005 (20 days in total). The data were downloaded from the BHL website (BHL, 2009). Following Qiu et al. (2009), the downloaded data were further filtered and aggregated into 20-sec resolution. The processed dataset included flow, mean speed and density at each detector station.

Figure 6.2 and Figure 6.3 show respectively the speed profiles measured at the BHL stations on I-80E and I-80W on a normal weekday, 7 December 2005 (Wednesday) from 0:00 to 23:59. Those 'zero speeds' (in particular before 05:00 of the day) mean that there was no traffic measured during the associated time interval. For I-80E, congestion started building up at 15:00 and then recovered at around 19:00, associated with the evening commute from San Francisco and Oakland to East Bay Area. For I-80W, Figure 6.3 shows that the freeway was congested most of the time due to both morning and evening commutes. The I-80W freeway heads to the MacArthur Maze located at the eastern end of San Francisco-Oakland Bay Bridge. The MacArthur Maze is the interchange of three major freeways (I-80, I-880, and I-580) and is a major bottleneck in the Bay Area. Congestion at the Maze often spills over to the upstream and affects the traffic flow.

Figure 6.1 Berkeley Highway Laboratory test site (source: Google Maps)

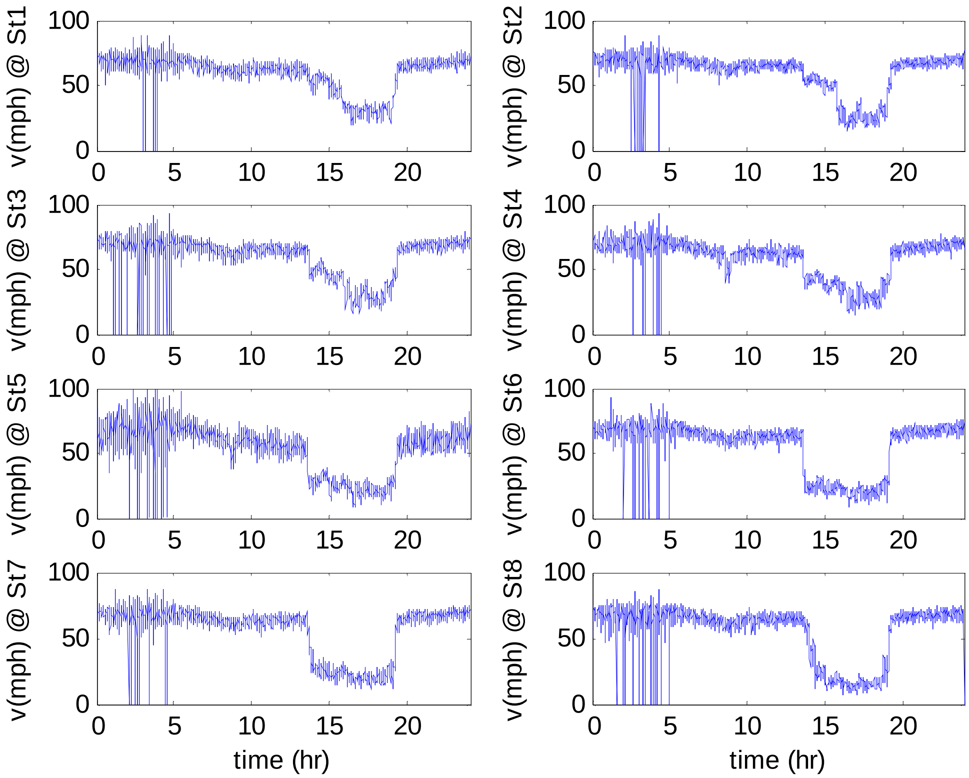

Figure 6.2 Speed profiles at BHL stations on I80-E, 7 Dec. 2005

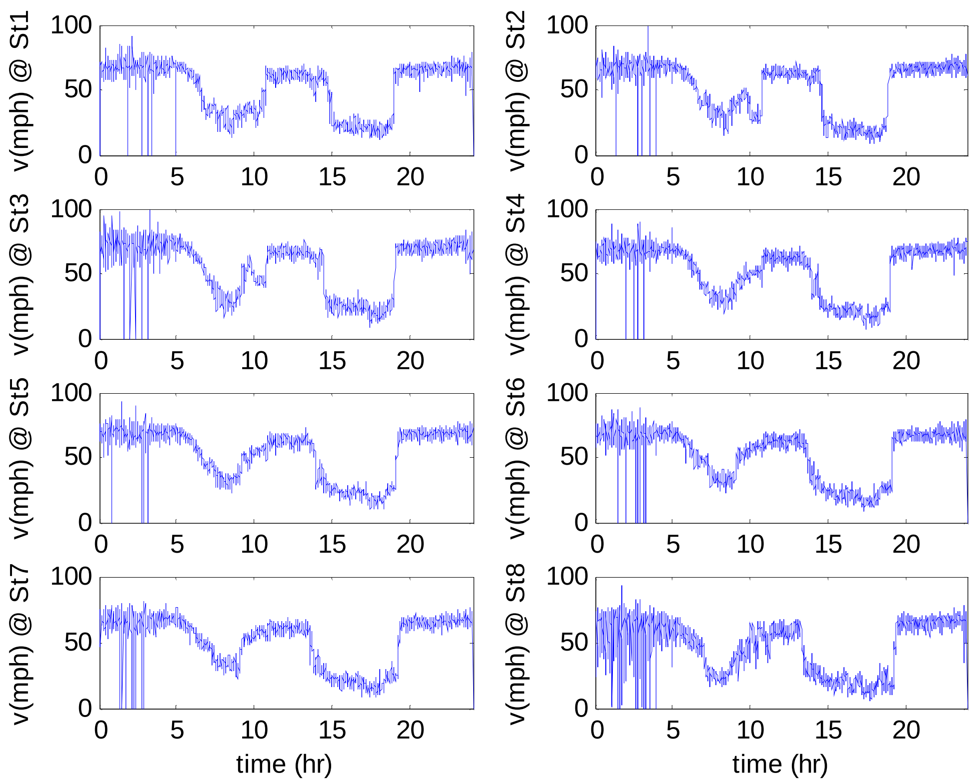

Figure 6.3 Speed profiles at BHL stations on I80-W, 7 DEC 2005

6.3. Defining and analyzing traffic breakdown

Adopting a sensible definition of traffic breakdown is vital for the present analysis. This section presents and discusses four different definitions of traffic breakdown. We start with reviewing Brilon's (2005) approach, which is regarded as Method 1 in this section. Three alternative definitions (Methods 2, 3, and 4) are then presented. The plausibility of these definitions of breakdown is discussed.

6.3.1. Method 1: Brilon's (2005) Approach

Brilon's definition of breakdown was adopted by a number of others (see for example, Cambridge Systematics, 2005, pp. 2-22; Dowling et al., 2008) due to its simplicity. Brilon et al. (2005) classified the traffic data into the following three categories:

- Case 1: $v(t) > v^*, v(t+1) < v^*$
  Traffic at the current time *t* is regarded as a realization of traffic flow causing breakdown.

- Case 2: $v(t) > v^*, v(t+1) > v^*$
  It implies the system is able to accommodate the current traffic state.

- Case 3: $v(t) < v^*$
  Traffic at the current time is in congestion. The associated traffic data is discarded as it contains no useful information for analysis.

The notation $v(t)$ represents the average speed measured at the detector station during time interval t; v^* is the speed threshold that defines traffic breakdown. Brilon et al. (2005) set this threshold to be 70 km/h (~45 mph). Brilon et al. (2005) argued that the speed threshold of 70 km/h was found to be fairly representative for German freeways, although it can be different for different situations. Dowling et al. (2008) investigated the traffic data collected from freeways I-80 and US-101 in the San Francisco Bay Area, and set the speed threshold v^* to be 45 mph, which is close to the one suggested by Brilon et al. (2005). In fact, the speed 45 mph is also the threshold suggested by the Federal Highway Administration for defining traffic congestion (see Cambridge Systematics, 2005, pp. 2-22).

To analyze Brilon's definition of breakdown, we first derive in Figure 6.4 the distribution of traffic states on a fundamental (flow-density) diagram. It is noted that the x and y axes are referring respectively to the average flow and density on one lane. For brevity, we only used data collected at Station 1 on I-80E. It is also noted that only the peak period (15:00 – 19:00 for I-80E) was considered as we are only interested in peak periods. Nevertheless, we believe this should not lose the generality of the analysis. The diagram was constructed as follows: the flow-density (q-k) diagram is first discretized into 'boxes' with dimension Δq by Δk, where Δq is 100 vphpl and Δk is 1 vpmpl. We then denoted each box in the diagram by $(\bar{q}, \bar{k})$, where $\bar{q}$ (flow) is a multiple of 100 between 0 and 2,200 (vphpl) and $\bar{k}$ (density) is an integer between 0 and 100 (vpmpl). Given the BHL dataset of traffic flow q and density k, a sample point (q,k) was allocated to box $(\bar{q}, \bar{k})$ if $\bar{q} - \Delta q < q \le \bar{q}$ and $\bar{k} - \Delta k < k \le \bar{k}$. The shade of each box in the figure represents the number of sample points in that box. It can be seen from Figure 6.4 that the samples clustered at free flow (density less than 30 vpmpl) and congestion (density between 45 vpmpl and 60 vpmpl), while relatively less data were observed around the capacity region of the flow-density diagram (with density around 35 – 40 vpmpl, flow 2,000 vphpl).

To investigate the distribution of breakdown events in the flow-density diagram, we calculated the *conditional* probability that a breakdown $\mathbf{B}$ occurs in each box $(\bar{q}, \bar{k})$, in which

$$p[\mathbf{B}(\bar{q}, \bar{k}) \big| (\bar{q}, \bar{k})] = \frac{\text{total number of breakdown events in box } (\bar{q}, \bar{k})}{\text{total number of sample points in box } (\bar{q}, \bar{k})}. \tag{6.1}$$

An extreme case, where $p[\mathbf{B}(\bar{q}, \bar{k}) \big| (\bar{q}, \bar{k})] = 1$, implies that a breakdown definitely occurs in $(\bar{q}, \bar{k})$.

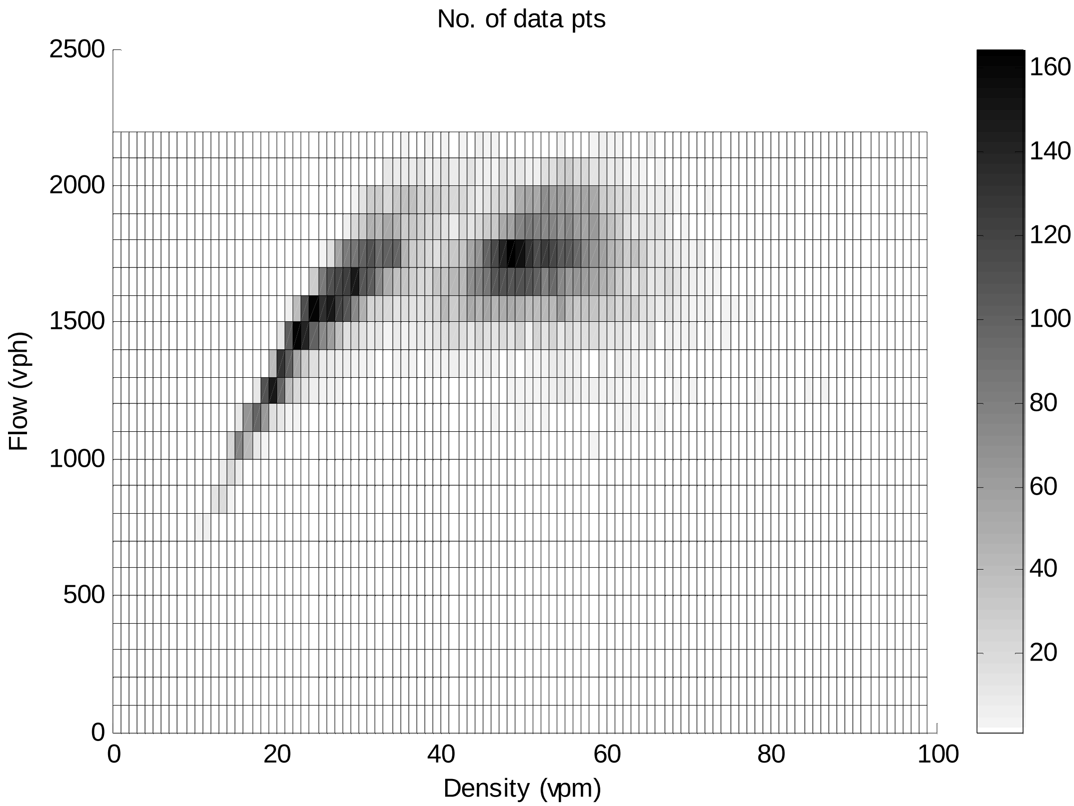

Figure 6.4 Distribution of sample points at Station 1 on I-80E (data resolution: 20 sec)

Figure 6.5 shows the distribution of breakdown events on the flow-density diagram following Brilon's definition. The darker the box, the higher the breakdown probability $p[\mathbf{B}(\bar{q},\bar{k})\big|(\bar{q},\bar{k})]$ and hence more likely that the associated traffic state will induce a breakdown. With Brilon's definition, a breakdown is only counted when the mean speed of approaching traffic is above the speed threshold, 45 mph. As a result, breakdown events were only observed on the left limb (uncongested part) of the diagram but none on the right limb (congested part) as shown in Figure 6.5. This gave us no information on the transition from congested flow to standstill (speed < 30 mph). Indeed, understanding the transition from moderate congestion to complete standstill is important for implementing traffic control (see Kerner, 2004; Lu et al., 2009). As our ultimate goal is to derive traffic control strategies that can function under a wide range of scenarios rather than simply under uncongested state, we need to have a better definition of breakdown to capture the entire flow-density diagram.

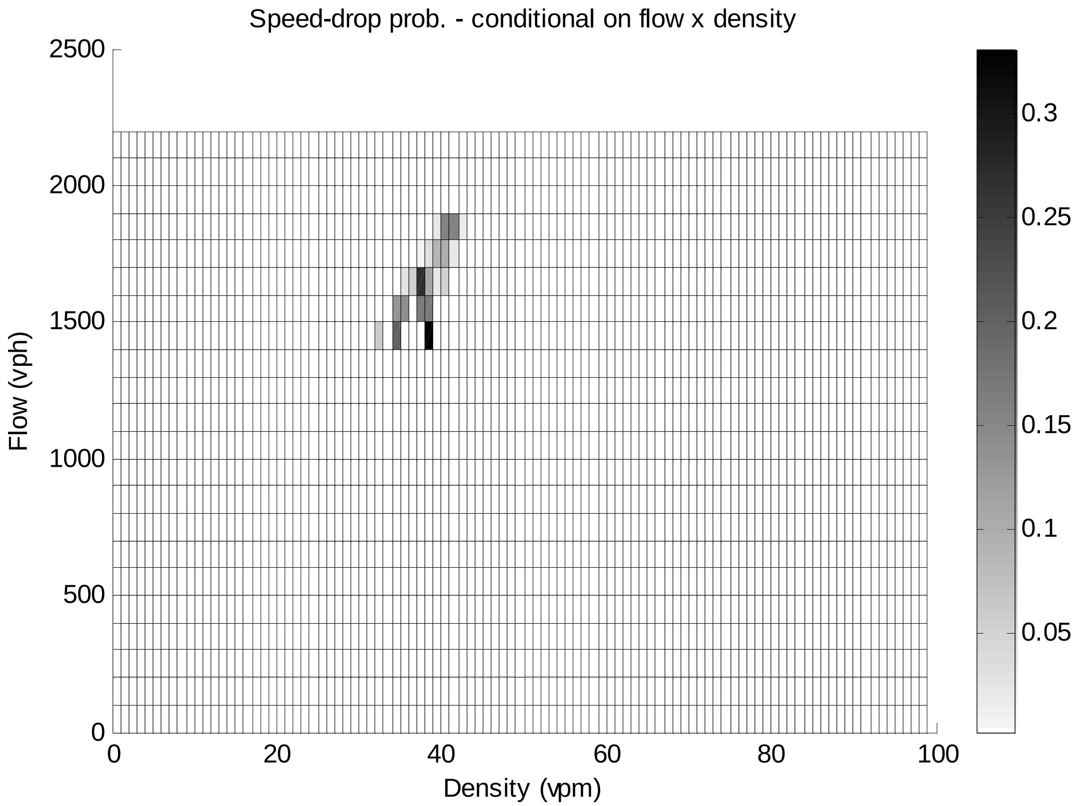

Figure 6.5 Distribution of breakdown events at Station 1 on I-80E (data resolution: 20 sec)– Method 1

6.3.2. Method 2: speed-drop between two successive time intervals

This section presents an alternative breakdown definition (called Method 2) based on the speed change between two successive time intervals, regardless of the magnitudes of the speeds. One advantage of Method 2's definition is that all speeds can be considered instead of only speeds above the predefined threshold as in Method 1. Nevertheless, it is also noted that Method 2 is more sensitive to data noise than Method 1. To reduce the effect of data noise, the 20-sec traffic data (including flow, density, and speed) were first 'smoothed' by using a 5-min moving average data smoother[1]. With the same dataset (Station 1, I80E) as in the previous section, Figure 6.6 shows the distribution of the smoothed sample points. Comparing Figure 6.6 with Figure 6.4, it is observed that the variability of the smoothed data was reduced.

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[1] In general, data smoothing is a technique to capture important patterns in the data, while leaving out noise and other fine details. Nevertheless, data smoothers can also mask important information in data, which will be discussed further in Section 6.3.4. Further detail about data smoothers can be referred to Wikipedia (2009).

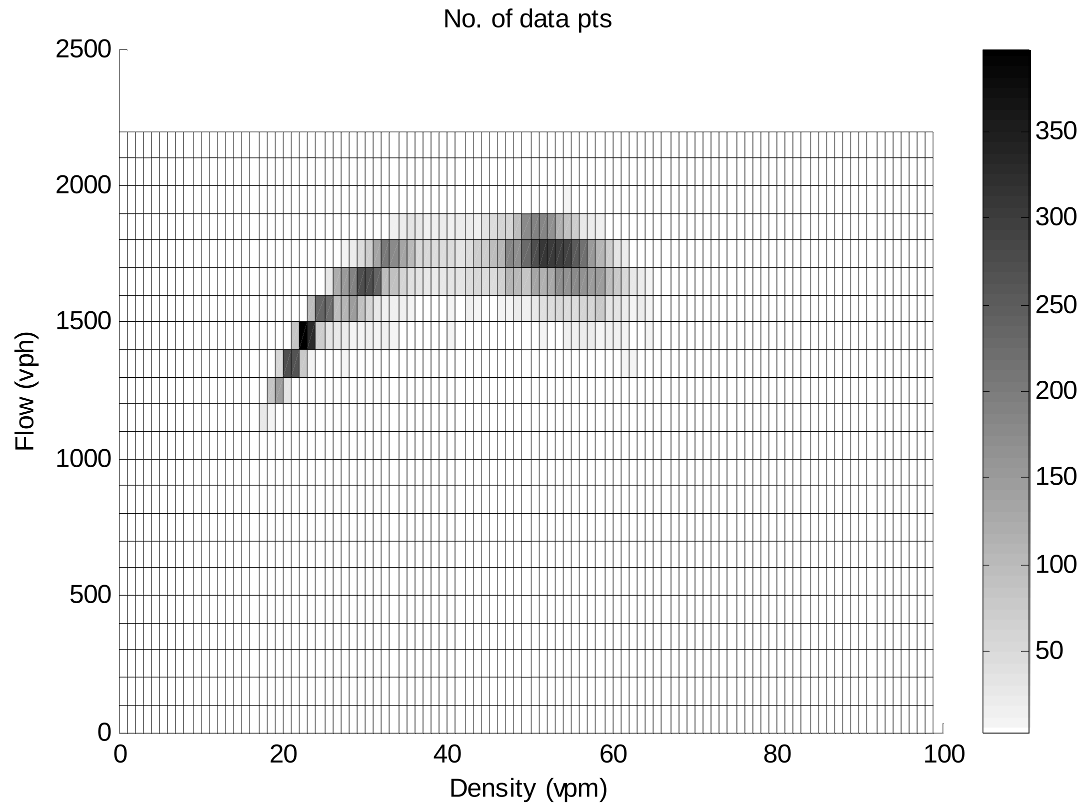

Figure 6.6 Distribution of smoothed sample points at Station 1 on I-80E (data resolution: 20 sec)

The smoothed data are then classified into the following two categories:

- if: $\hat{v}(t) - \hat{v}(t+1) > \Delta v^*$,
  traffic at the current time *t* is regarded as a realization of traffic flow causing breakdown;
- else, the system is considered to be able to accommodate the current traffic state.

The notation $\hat{v}$ is the smoothed speed profile; Δv^* is the speed drop threshold that defines traffic breakdown. After a series of numerical experiments, we defined this Δv^* as the maximum of 3 mph and 10% of the original speed. The '10%' criterion is used to accommodate the higher variance in speed under free-flow while the '3 mph' is for the low speed variations in congestion.

Figure 6.7 shows the distribution of breakdown events with Method 2's definition. As mentioned, with such definition of breakdown we can cover the entire flow-density diagram. However, it is noticed that the breakdown events clustered at moderate density (around 35 vpm) and low flow (around 1,500 vph, refer to the rectangle in the diagram). Suppose that the density of approaching traffic is 35 vpm (see Figure 6.7), the probability of breakdown of approaching flow at 1,500 vph will be higher than that at 1,800 vph. This implies that traffic approaching at a lower speed (1,500/35 = 43 mph) will have a higher probability to induce a breakdown than traffic approaching at a higher speed (1,800/35 = 51 vph). Such implication does not appear to be plausible and this implausibility can be explained as follows: in reality, it is understood that traffic breakdown is usually a *process* that lasts for some time rather simply two time intervals. Consider a traffic state with speed v_1 triggers a breakdown process in which the traffic speed drops from v_1 to v_5 consecutively for five time intervals. Denote v_i as the speed at the *i*-th time interval, where $v_1 > v_2 + \Delta v^* > v_3 + \Delta v^* > v_4 + \Delta v^* > v_5 + \Delta v^*$. According to Method 2, such breakdown process will be represented by four distinct breakdown events with associated breakdown speeds v_1, v_2, v_3, and v_4 instead of the true breakdown speed v_1. The average of the 'perceived' breakdown speeds in such case will then be $\frac{v_1 + v_2 + v_3 + v_4}{4} < v_1$. As a result, it is not surprising that Method 2 could underestimate the traffic speed causing breakdowns.

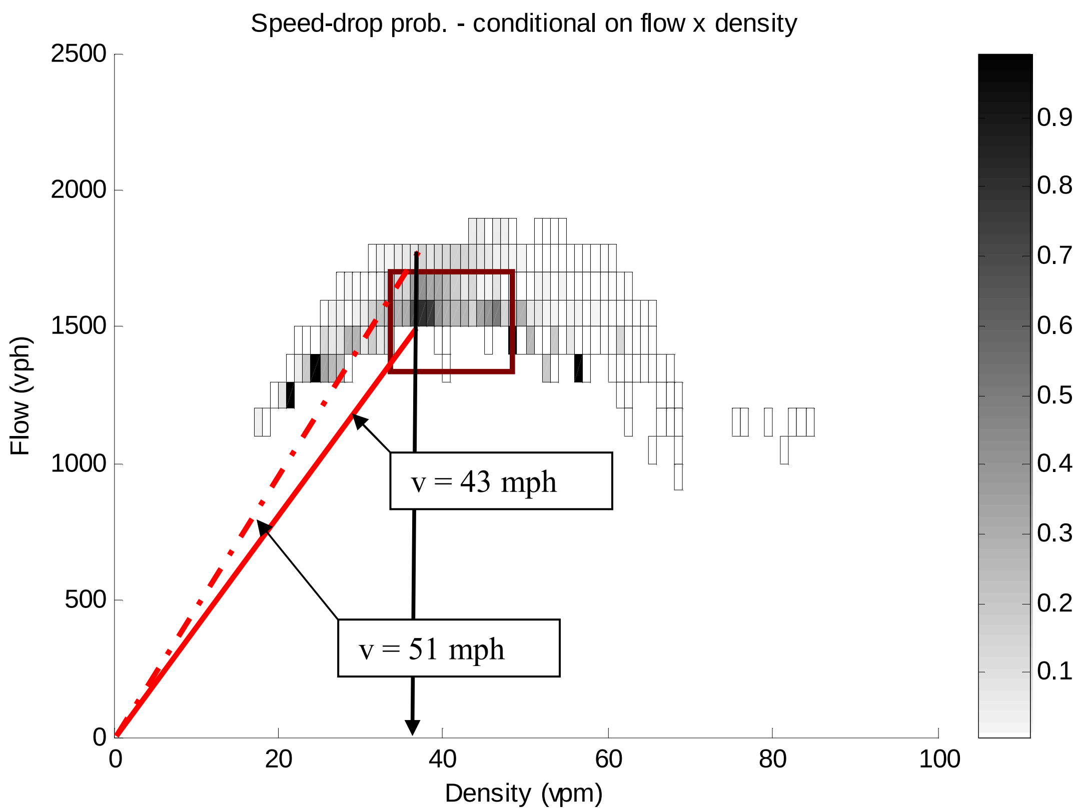

Figure 6.7 Distribution of breakdowns – Method 2

6.3.3. Method 3: speed drop as a process

To modify Method 2, we formulate another definition (Method 3) which considers breakdown to be a process instead of simply an event between two consecutive time intervals. Method 3 also requires a data smoother for the same reason as Method 2. After data smoothing, we located the 'peaks' and 'valleys' in the smoothed speed profile. A peak is regarded as a 'breakdown' point if the speed difference between that peak and its immediately following valley is higher than a predefined threshold. The threshold was set to be 5 mph in this study. It is also required that the associated traffic density during the transition has to be non-decreasing. This additional condition on density is to ensure that the speed-drop is due to the build-up of congestion rather than random noise.

Figure 6.8 shows the distribution of breakdown events with Method 3's definition. Method 3 is a better representation of traffic physics than Method 2, but Method 3 involves a number of operations in implementation and hence is less efficient than the previous methods. Moreover, there were only a few useful statistics obtained from this method due to the strict criteria defining breakdown. Consequently, Method 3 may not be a good definition of breakdown to use in practice due to its inefficiency.

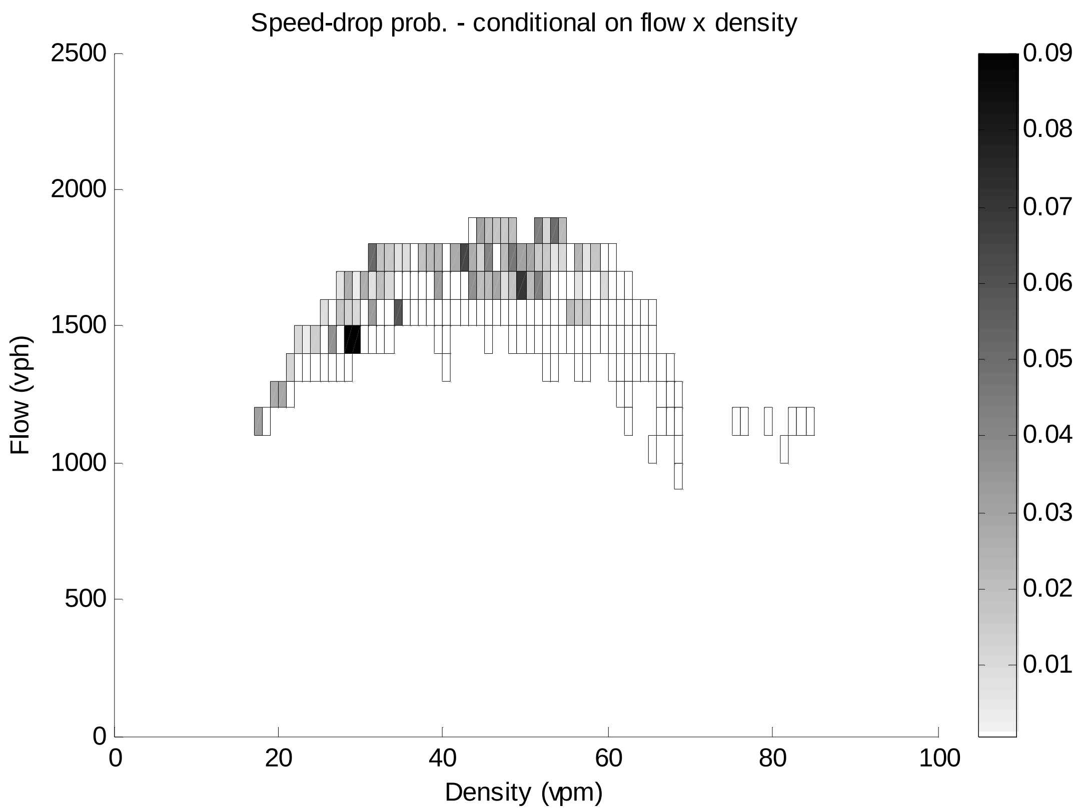

Figure 6.8 Distribution of breakdowns – Method 3

6.3.4. Method 4: speed-drop process based on total variance within a moving window

The drawbacks of Method 2 and Method 3 are implausibility and inefficiency respectively. Moreover, both Method 2 and Method 3 require the data to be smoothed. Considering that the data smoother may mask important information in data, this section proposes a method (Method 4) that can function without using a data smoother. Method 4 can also be implemented in a more efficient and plausible way compared to Methods 2 and 3.

A moving time window, T, is first defined. We set this time window T to be 5 minutes. A traffic state at time t is then said to induce a breakdown:

- if: $\sum_{s=t}^{t+T} \Delta v(s) > \Delta v^*$,
  where $\Delta v(s) = v(s+1) - v(s)$, s is a time interval in which $t \le s \le t + T - 1$;

- else, the system is considered to be able to accommodate the current traffic state.

The notation Δv^* is the speed-drop threshold for breakdown. We set this threshold to be 5 mph. In fact, Method 4 can be regarded as a modification of Method 2. Instead of looking at speed change simply between two time intervals, Method 4 considers an 'aggregated' speed change (total variance) over a longer time period and thus reduces the effect of noise implicitly by 'aggregation'. The distribution of breakdown events is plotted in Figure 6.9. The breakdown events were observed around the capacity region and the moderately congested region on the Fundamental Diagram. The lower breakdown probability region at moderate density (~ 40 vpm) is due to the fewer sample points in that region. Due to its plausibility and efficiency, we select Method 4 as the definition of breakdown for the rest of the study presented here.

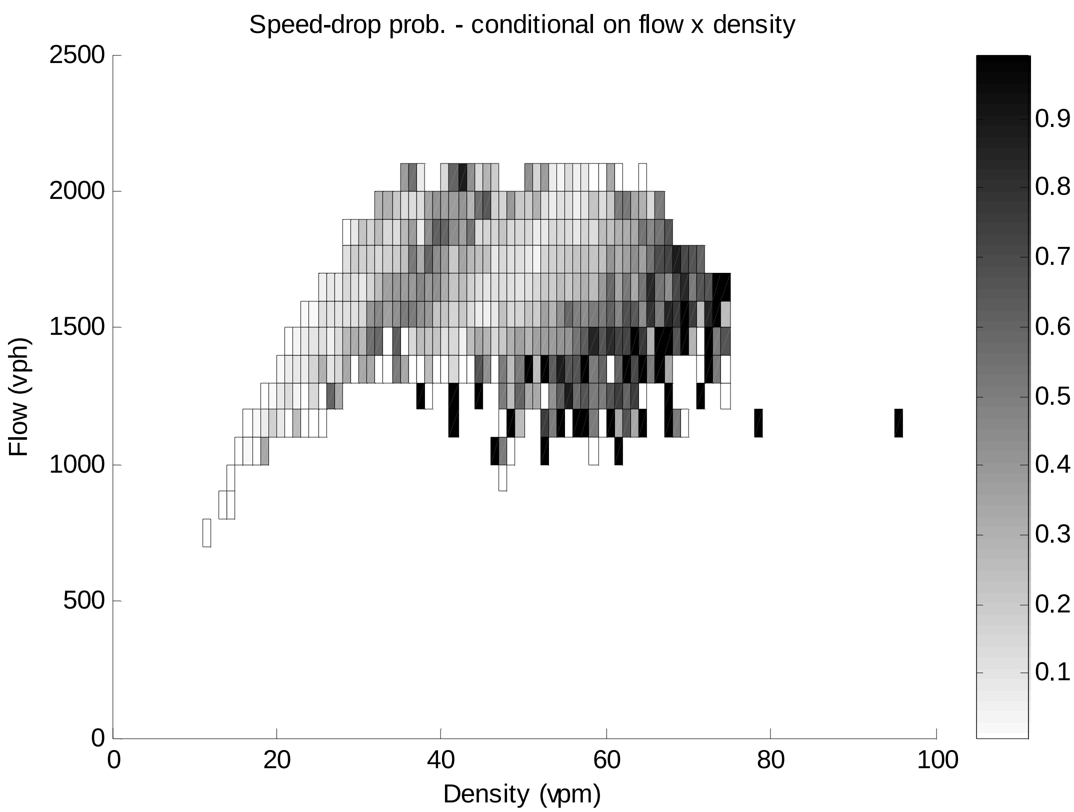

Figure 6.9 Distribution of breakdowns – Method 4

6.4 Application to variable speed limit and ramp metering control

The design of variable speed control and ramp metering can be formulated as an optimal control problem with an objective to maximize total benefit of the system (e.g., to minimize the total system travel time) subject to a set of constraints. The constraints include traffic dynamics and bounds on the control variables (i.e., speed and density of traffic). The results derived from this study can be used to define the bounds on the control variables such that the *cumulative* probability of traffic breakdown is less than a predefined threshold.

We calculate the following probability:

$$p[\mathbf{B}(\bar{v},\bar{k})] = \frac{\text{total number of breakdown events in } (\bar{v},\bar{k})}{\text{total number of data points in the entire sample space}}\,, \tag{6.2}$$

in which $\bar{v}$ and $\bar{k}$ are the mean speed and density of the approaching traffic respectively. Following the discussion in Section 6.3, breakdown is defined according to Method 4. It should be noted that the probability in (6.2) is different from (6.1). The probability in (6.1) is conditional on the approaching traffic state, while (6.2) is unconditional. The denominator in (6.2) is the total number of data points in the entire sample space. Unlike the probability in (6.1), the denominator is common for all $p[\mathbf{B}(\bar{v},\bar{k})]$. For example, if we consider 5-day, 24-hour data at 20-sec resolution, the denominator in (6.2) will be 5x24x60x60/20 = 21,600.

The cumulative breakdown probability is then derived as

$$P[\mathbf{B}(\bar{v},\bar{k})] = \sum_{v=0}^{\bar{v}}\sum_{k=0}^{\bar{k}} p[\mathbf{B}(\bar{v},k)]\,. \tag{6.3}$$

The cumulative breakdown probability is understood as the probability of breakdown if the approaching mean speed and density are less than $\bar{v}$ and $\bar{k}$ respectively.

The probability (6.3) can be plotted in contours with respect to the associated speed and density of approaching traffic. As an illustration, Figure 6.10 and Figure 6.11 show respectively the breakdown probability contours derived from data at Station 1 on I-80E and Station 5 on I-80W. In the figures, each combination of speed and density of approaching traffic on the same contour has the same probability of inducing breakdown. The contours are plotted up to the maximum speed and density (65 mph, 60 vpmpl in Figure 6.10; 70 mph, 70 vpmpl in Figure 6.11) that were observed to induce a breakdown.

Each contour line can be approximated by linear functions of control speed and density. The linear functions can then be used as constraints on the control variables such that the breakdown probability at the section of interest is bounded below a certain value. For example, suppose that the traffic density per lane measured at Station 1 on I-80E is 58 vpmpl and it is desired to have the breakdown probability below 10% at the location (see Figure 6.10). The speed of the mainline traffic should then be controlled at 45 mph.

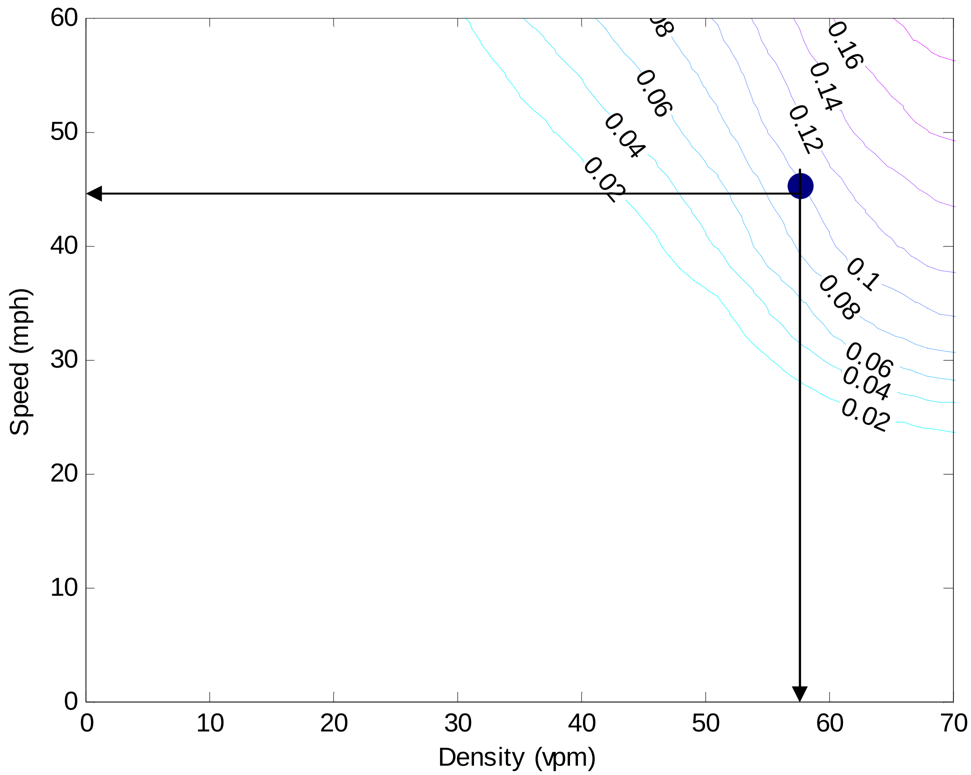

Figure 6.10 Contour of breakdown probability within 5 min – I-80E: Station 1

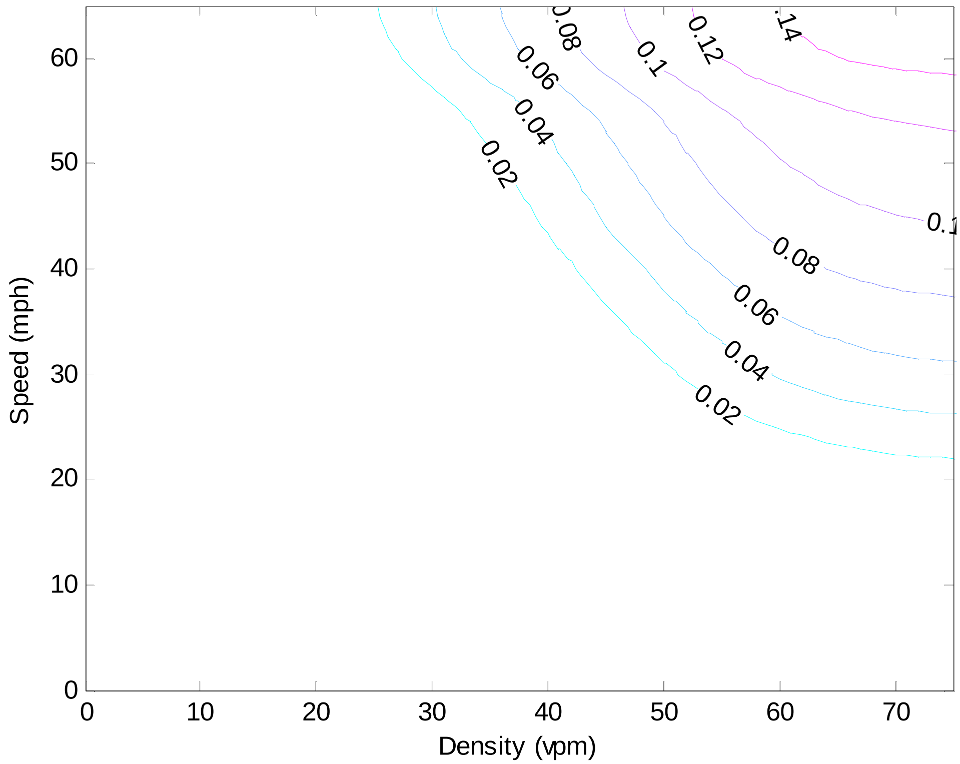

Figure 6.11 Contour of breakdown probability within 5 min – I-80W: Station 5

6.5 Conclusions

This chapter presents an empirical study of traffic congestion as part of a larger study aimed at developing variable speed limit and ramp metering control. It is concluded that Method 4 is the most suitable way to define and analyze traffic breakdown. Following the definition, the probability of breakdown is derived as a bivariate distribution of average speed and density of incoming traffic.

A case study is performed on a section of Freeway I-80 in the San Francisco Bay Area using Berkeley Highway Laboratory (BHL) data. Contour plots of breakdown probability are also derived at the BHL detector stations. Those contour plots are useful for developing variable speed control and ramp metering strategies. Design of variable speed limit and ramp metering can be formulated as an optimal control problem with an objective to maximize total benefit of the system (e.g. minimizing the total system delay) subject to constraints on the control speed and density of approaching traffic. The results of this analysis can be used to construct bounds on speed and density such that the traffic breakdown probability is confined below a specified threshold, say 10%. This analysis thereby contributes to the understanding of traffic congestion and design of freeway control strategies.

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Chapter 7. Analysis of ACC and CACC Vehicle Data

7.1 Experimental Protocol

The experimental protocol was designed to evaluate the perceived acceptability of the shorter gap settings offered by the CACC system using an on-the-road, in real traffic, study design. Although the goal of the experiment was to test the shorter gaps provided by the CACC system, most drivers in the U.S. are unfamiliar even with the already available ACC systems that are currently on the market. At the time of this study, ACC systems were generally only available on high-end, luxury cars, and often as a fairly expensive option, resulting in a very small market penetration. Thus, the experimental protocol that was developed needed to first allow the test participants enough time to get acquainted with a standard ACC system before the testing of a CACC system could begin.

The experimental protocol was split into two phases. (See Table 7..) In the first phase, the test participants were given the silver Infiniti FX45 with the factory installed ACC system to drive as their own (without an experimenter present) for a period of about 11 days. During that period, there were roughly 7 week days where the test participant would be commuting to and from work with the vehicle and 4 weekend days where the test participant was free to use the vehicle wherever they were going. Additionally, there were minor variations between participants. As an example, some participants had the car delivered on Thursday morning, making Friday the baseline day.

The second phase of the experiment lasted for two days, immediately following the last day of the first phase. In this phase, the test participant drove the copper Infiniti FX45 with the CACC system for their morning and evening commutes. During these four trips an experimenter was present in the vehicle with the test participant, and the silver Infiniti FX45 was driven by a confederate to play the role of the lead vehicle during the commute. Additionally, sometimes the CACC testing days ended up falling on Tuesday/Wednesday instead of Monday/Tuesday due to the holidays or other variations in the participant's work schedule.

Table 7.1: Summary of testing condition per day.

	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday
Week 1	Vehicle delivered	Day 1 No ACC	Day 2 ACC	Day 3 ACC	Day 4 ACC	Day 5 ACC	Day 6 ACC
Week 2	Day 7 ACC	Day 8 No ACC	Day 9 ACC	Day 10 ACC	Day 11 ACC	Day 12 CACC	Day 13 CACC

After the fourth participant, there was a slight change to the second phase protocol to add a short CACC practice session before conducting the CACC testing during the participant's morning and evening commutes. The half-hour CACC practice session was conducted at the participant's convenience between days 8 and 11. The purpose of this practice session was simply to familiarize the participant with the CACC system. This additional practice session was added because it subjectively seemed like it took the participants about a half hour to get comfortable with the CACC system, and this learning effect might have been influencing the first CACC testing day.

The CACC driving sessions took place on public highways on the routes designated by the participants. Thus, the CACC testing was all done on routes with which the participants were already familiar. The test participants were informed that they could stop at any moment or choose any route that they desired, but they were asked to drive in accordance with all state and local driving laws.

7.1.1 Participant Recruitment

To be eligible to participate in the study, potential candidates needed to meet the following criteria:

- 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 traveling 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 initial test participants were recruiting using the U.C. Berkeley and U.C. San Francisco Research Subject Volunteer Program, which is a basically a website bulletin board where potential participants can browse studies which are currently seeking volunteers. After an experimenter validated a candidate participant's eligibility, either through a phone call or email, a participant packet was mailed to the participant. The packet contained a cover letter, study consent forms, and a DMV records release form (to verify the candidate's eligibility to participate). A potential participant's DMV records were checked either by having the participant mail the DMV directly and obtain a copy of their records or by consenting to have California PATH check their DMV records electronically using the Volunteer Select Plus service available from LexusNexis Risk & Information Analytics Group, Inc.

As part of the consent form package, there were three documents that needed to be signed by the participants. The first document provided participants with informed consent regarding their participation in the study. This document detailed the study, providing the participants with enough information to make an informed decision about whether or not they still wanted to participate in the study. Informed consent on this form was mandatory for participation. The second document was a video and photographic image release form which allowed participants to designate appropriate uses for any images collected during the study. Finally, there was a fuel card user agreement, which was only required if the participant wished to use a University provided fuel card to purchase gas for the vehicle. It was not required if the participant wished to purchase fuel on his or her own and submit receipts for reimbursement at the end of the study. The participants generally had several weeks to review the consent materials and ask questions, as the forms were not signed until the day that the vehicle was dropped off with the participant.

7.1.2 Phase 1: Gaining Experience with ACC Systems

The goal of the first phase of the experiment was to allow the driver to acclimate to the test vehicle and to gain experience with a typical ACC system, since it was assumed that most drivers in the US would be unfamiliar with such a system. The first phase also allowed for the collection of baseline driver behavior data during two days when the test participant was asked to drive the vehicle without using the ACC system. This phase of the protocol could further be broken into five steps over 11 days.

7.1.2.1 Step 1: Vehicle Delivery

After a potential participant's eligibility to participate in the experiment was verified, a testing date was scheduled, and the vehicle was delivered to the participant's place of residence or work by an experimenter on either a Wednesday or a Thursday. At the time of delivery, the experimenter completed a vehicle checkout checklist, and trained the test participant in the features of the vehicle and the use of the ACC system.

The first part of the training took place when the vehicle was parked. The experimenter explained the ACC functions, how to activate them, and how to turn them off. The test participant was invited to ask questions throughout this step.

The second part of the training involved taking the vehicle on a highway for a short trip with the experimenter in the passenger seat. The participant was then instructed to turn the ACC system on whenever he or she felt comfortable to do so. The experimenter then talked the participant through the features of the system and answered any additional questions that the driver had about the system. The experimenter also stressed the following important parts of the experimental protocol to the test participant.

- The participant was the only person allowed to drive or ride in the vehicle.
- The participant was to try to use this vehicle as he/she would use their personal vehicle.
- The participant should try to use the ACC when conditions allowed (highway driving with relative free flow traffic) as much as possible on the non-baseline days of the protocol.
- The participant was encouraged to try the different gap settings until finding one with which they were comfortable.
- The participant was reminded to fill out a logbook entry for each trip taken in the vehicle. (See Appendix C for a copy of a typical logbook entry.)

7.1.2.2 Step 2: One Baseline (Non-ACC) Driving Day

On Day 1, the first full day with the ACC equipped vehicle (which was typically a Thursday), the test participant was instructed to drive the vehicle without using the ACC system. Although the participant was not actively using the ACC system, the DAS was still recording all of the data that would normally be collected when the ACC system was active. The data collected from this day was then used as a baseline to characterize the test participant's normal driving behavior.

7.1.2.3 Step 3: Six ACC Driving Days

After the baseline driving day, the participant was allowed to drive the vehicle for the next six days while freely using the ACC system. This would include four days of commutes and two weekend days of experience with the ACC system. Data from the vehicle's DAS was typically downloaded on day 6 while the test participant was at work.

7.1.2.4 Step 4: Second Baseline (Non-ACC) Driving Day

At this point, the test participant has had the ACC equipped vehicle for about a week. On Day 7, the second Thursday, the participant was again instructed to drive the vehicle without using the ACC system. This day served as a second baseline to allow for comparisons to be made between the participant's behavior before using the system and the participant's behavior after using the system to see whether or not the system had an influence on the participant's typical behavior.

7.1.2.5 Step 5: Three More ACC Driving Days

On Days 8 through 11, the test participant was again allowed to drive the vehicle using the ACC system. This would include one commute day and two weekend days. During this period of time, the participants were instructed to fill out the first survey on their experiences with the ACC system (see Appendix XX).

7.1.2.6 Phase 2: Using the CACC system

For most of the participants (excluding the first four), the second phase of the experimental protocol generally began with a half-hour practice CACC test drive. The experimenter and a confederate lead-vehicle driver generally met the test participant at his or her residence or place of work with the CACC equipped vehicle. The test participant then drove the CACC-enabled copper-colored FX45 with the experimenter present in the passenger seat, while the silver-colored FX45 was driven by the confederate driver to serve as the lead vehicle. The purpose of the practice session was to familiarize the participants with the CACC system. After a brief introduction to the differences between the ACC and CACC system while the vehicle was parked, a 15 to 30-minute practice drive was conducted on a nearby road selected by the participant. During the practice drive the participant was asked to try each of the new gap settings, as long as they felt comfortable, for a few minutes.

After the practice session, the protocol provided for two days (four commute trips) using the CACC system. For each CACC test trip, the experimenter and confederate lead-vehicle driver met the participant at their home or work with the CACC-enabled copper-colored FX45. Although an experimenter was present during this phase of testing, the participant still scheduled the times of departures, routes taken, and even the lane of travel. All of this was communicated to the lead vehicle driver via two-way radio. The experimenter also served as a safety observer since the CACC system was a prototype, and was only reliably capable of following the communication-enabled, silver-colored FX45. If the CACC system misbehaved or other vehicles cut in between the two test vehicles, the experimenter was able to turn the system off with a panic button which, in effect, mimicked the functionality of the CACC on/off switch.

At the end of the last day of CACC testing, the participant was asked their general impressions of the CACC system and given a survey on their experiences with both the ACC and CACC system to be completed and mailed back (see Appendix XX). The participants were then thanked and paid $100 for their participation in the experiment. They were also reimbursed for any fuel expenses incurred while in possession of the ACC equipped vehicle. The vehicles were then inspected and readied for the next participant.

7.2 Basic Statistics on the Pool of Test Participants

The sample was composed of 12 participants, 5 females and 7 males. Table 7. below provides the participants' characteristics.

Table 7.2: Test Participant characteristics.

Participant #	Age	Gender	Miles Driven Annually	One way Commute (home to work) in miles
1	32	F	10,000	24 miles
2	36	M	15,000	28 miles
3	40	F	15,000	37 miles
4	38	F	12,000	23 miles
5	45	F	24,000	33 miles
6	33	M	18,000	44 miles
7	35	M	25,000	43 miles
8	32	M	15,000	24 miles
9	29	M	15,000	29 miles
10	30	M	10,000	23 miles
11	27	F	18,000	30 miles
12	38	M	22,000	25 miles

The mean age of the sample of participant is 34.6 years (STD 5.12). The mean annual mileage is 16,583 miles/year (STD 5017), and the average daily commute, one way, is 30.25 miles (STD 7.5).

As a reminder, the overall test plan aims to reach a total of 16 participants, equally balanced on gender and part of one age group ranging from 30 to 45 years of age. The analysis of the results for the remaining four test participants will be completed within the next phase of the project.

7.3 Data Collected on Vehicles

There were two types of data files generated by the ACC/CACC vehicle's Data Acquisition System (DAS). First, the vehicles generated engineering files, collected and stored on the engineering computer installed each vehicle. Second, the vehicles generated two digital video files from the five onboard cameras, which were stored on a separate video collection computer. Two paper questionnaires were also administered during the experiment regarding driving practice and ACC/CACC usage.

7.3.1 Engineering files

The engineering files are essentially text files containing rows and columns of numerical vehicle data such as speed, distance, latitude, longitude, etc. Data were recorded every 50 ms (20 Hz sampling rate) and the files were saved every two minutes. There were three types of engineering files that were recorded by the DAS and their contents are described in Tables 8.3 through 8.5. Although it may seem trivial, much effort was put into creating a file naming method that would ensure that each file contained a unique name, thus avoiding any potential to accidently overwrite data when it is copied or moved. The engineering filenames were constructed using the following convention:

[V][F][MMDD][TTTT][SSS].dat

where:

- [V] is a single character representing the vehicle on which the data is collected:
  - 'c' is used for data from the copper car, equipped with the CACC prototype
  - 's' is used for data from the silver car, with the commercial ACC
- [F] is a single character representing the type of data that will be contained within the file:
  - 'a' is used for C/ACC data
  - 'c' is used for communication from the lead vehicle data
  - 'd' is used for driver behavior and target data
- [MMDD] is the date with 2 characters for month and 2 characters for the day of the month
- [TTTT] is a 4-digit Trip ID number which is incremented each time the vehicle is started
- [SSS] is a 3-digit sequence number which starts at 000 and increments every 2 minutes

When the engineering files are downloaded from the vehicle, they are grouped into the concept of a trip, where a trip corresponds to each time the vehicle ignition was switched on. The files are copied into a single trip directory which is named using the following convention:

e[YYMMDD][TTTT]

where:

- 'e' is the indication that the directory contains engineering (instead of video) data
- [YYMMDD] is the trip date with 2 digits representing year, month, and day
- [TTTT] is a 4-digit Trip ID which matches the trip ID number of the enclosed files

Table 7.3: Contents of the 'a' File (CACC Data)

Column		Description	Unit/Range
1	A	Time of day this entry was recorded	hh:mm:ss.sss
2	B	Number of seconds since start of process	sec
3	C	Virtual pedal position (from driver, ACC or CACC)	percent
4	D	Engine RPM	rpm
5	E	Mean effective torque	Nm
6	F	During shift (no/yes)	0/1
7	G	Current gear	0-7
8	H	Front right wheel speed	rpm
9	I	Brake pressure	bar
10	J	Change counter	0-7
11	K	Output Shaft revolution rate	rpm
12	L	Turbine revolution rate	rpm
13	M	Target engine torque	Nm
14	N	Target lock	0/1
15	O	Virtual distance (CACC output command)	m
16	P	Virtual speed (CACC output command)	m/s

Table 7.4: Contents of the 'c' File (Communication Data)

Column		Parameter	Units
1	A	Time of day this entry was recorded	hh:mm:ss.sss
2	B	Number of seconds since start of process	sec
3	C	Time wireless comm message sent	sec
4	D	Time wireless comm message received	sec
5	E	Time engineering message sent	sec
6	F	Time engineering message received	sec
7	G	Message count	0-255
8	H	My time	msec
9	I	Accelerator pedal position (from driver)	percent
10	J	Virtual pedal position (from driver, ACC or CACC)	percent
11	K	Engine RPM	rpm
12	L	Mean effective torque	Nm
13	M	During shift (no/yes)	0/1
14	N	Current gear	0-7
15	O	Front right wheel speed	rpm
16	P	Driver braking (no/yes)	1/0
17	Q	Target lock	0/1
18	R	Car space (ACC gap selection)	1-3
19	S	Set speed	km/h
20	T	Brake pressure	bar
21	U	Distance from silver Nissan to target vehicle	m
22	V	Relative speed (between silver Nissan and its ACC target vehicle)	m/s
23	W	Yaw rate	deg/s
24	X	Vehicle Speed	km/h

Table 7.5: Contents of the 'd' File (Driver Behavior Data)

Column		Parameter	Units
1	A	Timestamp of file write	hh:mm:ss.sss
2	B	Number of seconds since start of process	sec
3	C	Time wireless comm message was sent	sec
4	D	Time wireless comm message was received	sec
5	E	Time engineering message was sent	sec
6	F	Time engineering message was received	sec
7	G	Yaw rate	deg/s
8	H	X-Acceleration	g
9	I	Y -Acceleration	g
10	J	ACC Active (off/on)	0/1
11	K	Car Space (ACC or CACC Gap Setting)	2-3-4-5 for copper 1-2-3 for silver
12	L	Target Approach Warning (false/true)	0/1
13	M	MainSW – ACC powered on (off/on)	0/1
14	N	ACC Buzzer - Master Alarm (off/on)	0/127
15	O	ACCBuzzer2nd - Target Approach Warning (off/on)	0/1
16	P	ACCBuzzer3rd	0/1
17	Q	ACC/CACC Set speed	km/h
18	R	Accel. PedalPosition (from driver)	percent
19	S	VirtualPedalPosition (from driver, ACC or CACC)	percent
20	T	Driver Braking (off/on)	1/0
21	U	ACCMainSW – ACC powered on (off/on)	0/1
22	V	Brake pressure	bar
23	W	Vehicle Speed	km/h
24	X	UTC Time	HHMMSS:ss
25	Y	Longitude	degree
26	Z	Latitude	degree
27	AA	Altitude	m
28	AB	GPS Speed Over Ground	km/h
29	AC	Numsats (number of GPS satellites available)	-
30	AD	Date	ddmmyy
31	AE	Change Counter	-
32	AF	Distance to Lead Vehicle	m
33	AG	Relative Speed Compared to Lead Vehicle (+ if closing gap / - if opening gap)	m/s

7.3.2 Video Files

Video data were recorded continuously from five cameras into two divx digital video files at a rate of 500 kbps. The files were roughly two minutes long such that the ends of the video files were synchronized with the ends of the corresponding engineering files. Unfortunately, due to technical constraints and some level of randomness with the time it takes to open a new video file in real time, the beginnings of the video files are not necessarily synchronized with the beginnings of the engineering files. The video files typically contain an additional 1 to 2 seconds of video at the beginning to avoid the possibility of a loss of video.

Figure 7. illustrates the views provided by each of the two video file types. The image on the left is the front scene from a single forward looking camera. At the bottom of the image is the time, in hours, minutes, seconds and milliseconds and the date. The image on the right is a composite of 4 cameras using a video quad splitter. In the top left corner is the rear view. In the top right corner is a view of the steering wheel. In the bottom left corner is a view of the driver's right foot above the accelerator and brake pedals, and finally, in the bottom right corner is a view of the driver's face.

Figure 7.1: Example of video file content (left is front view, right is quad view)

As with the engineering filenames, care was taken to ensure unique video filenames which followed the following naming convention:

[V][F][MMDD][TTTT][SSS].avi

where:

- [V] is a single character representing the vehicle on which the data is collected.
  's' is used for the silver car.
  'c' is used for the copper car.
- [F] is a single character representing the video file type or channel
  'f' represents the file containing the single video looking out of the front window
  'q' represents the file containing the four (quad) video images
- [TTTT] is a 4-digit Trip ID number which is incremented each time the vehicle is started
- [SSS] is a 3-digit sequence number which starts at 000 and increments every 2 minutes

Similar to the engineering files, the video data files were organized and copied into video trip directories. The video trip directories were named using the following convention:

v[YYMMDD][TTTT]

where:

- 'v' is the indication that the directory contains video data.
- [YYMMDD] is the trip date with 2 digits representing year, month, and day
- [TTTT] is a 4-digit Trip ID which matches the trip ID number of the enclosed files

7.4 Data Processing for Analysis

7.4.1 Data Downloading and Validation

For each test participant, between 8 and 11 GB worth of data were collected between the engineering and video files. There were a number of both automatic and manual steps or procedures that were required to retrieve the data from the vehicle DAS computers, verify its integrity, and move it to a RAID storage device where it could be archived and analyzed. On the vehicle DAS computers themselves, when a new trip was generated (each time the vehicle was started), the files for the last completed trip were automatically copied to a directory on the DAS video computer and put into a queue to be downloaded. When an external drive was attached to the video computer via USB, a script was activated which copied all of the data in the download queue to the external drive.

To assist in uploading the data from the USB drive to the RAID storage device, a data importing tool was written in the RealBasic programming language. The PATH Vehicle Data Import Tool served six functions and a screenshot is provided in Figure 7.:

1. The tool read the data on the USB drive and displayed the list of trips recorded by the DAS in a table that could be easily read by an analyst. The analyst could then cross-reference the trips that were downloaded from the vehicles with the paper trip logs kept by the test participants to determine whether or not data for any of the trips made by the participant were missing.
2. The tool allowed the analyst to filter out or skip the importing of inconsequential trips, such as short trips where the vehicle was simply moved or trips where the CACC vehicle was being driven by PATH researchers in order to meet the participants at their home or work before conducting the test.
3. The tool verified the integrity of the data on the USB drive by reporting the file counts for each expected file type and by checking the contents of the .dat files to search for parameters that do not appear to be updating. As shown in the provided figure, two of the trips returned errors with the accelerometer, suggesting that the device may have become unplugged.
4. The tool allowed an analyst to assign a Driver ID number to the trips as the data were being imported.
5. The tool imported (copied) the files from the USB drive to the RAID storage device, while both restructuring the directories and renaming the files to make subsequent data processing easier.
6. The tool created an import log file of all operations performed and errors encountered. The import log file detailed missing expected data or video files.

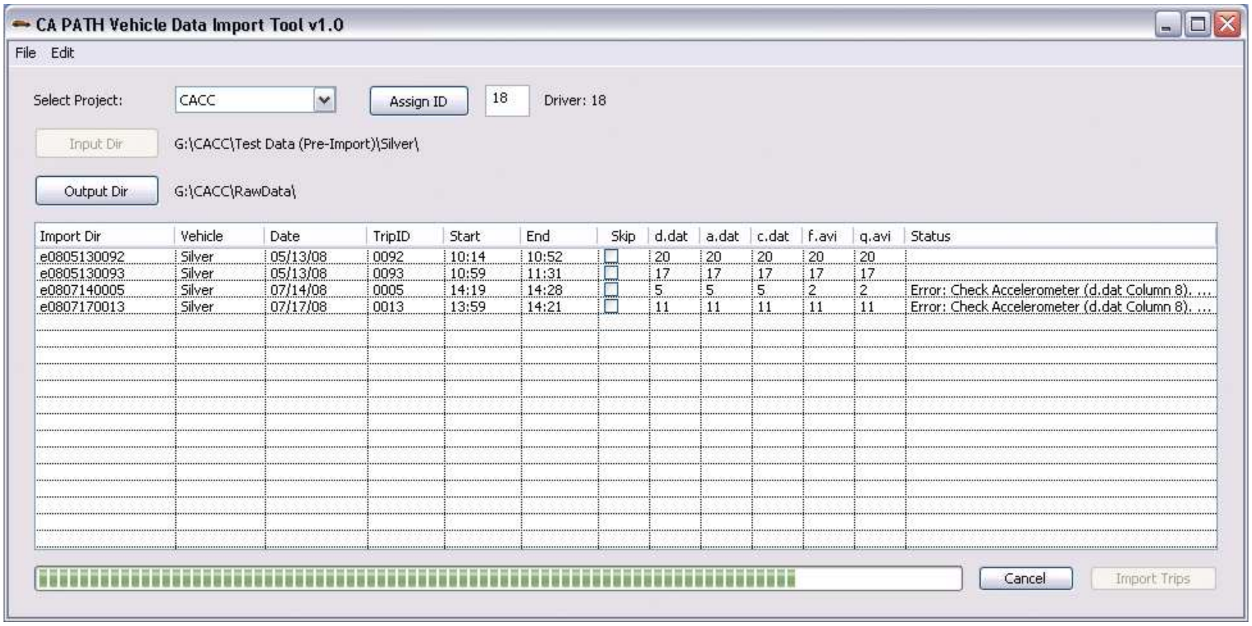

Figure 7.2: Sample screenshot of the CACC data import and validation tool

While the file naming conventions used on the vehicles were optimized to prevent the possibility of duplicate file names, the resulting filenames are a bit unwieldy for a person or analyst to visually parse and comprehend. As the files were imported to the RAID storage device, the directory structure and file names were changed to match the following conventions:

- Driver[XX]
  - [Vehicle]
    - Date[YYMMDD]
      - Trip[TTTT]
        - [SSS]
          - [V][F][TTTT][SSS].[EXT]

Where:

- [XX] is a two-digit test participant ID number
- [Vehicle] is the name of the vehicle from which the data was collected
  - 'Silver' is used for the silver ACC-enabled car
  - 'Copper' is used for the copper CACC-enabled car
- [YYMMDD] is the trip date with 2 digits representing year, month, and day
- [TTTT] is a 4-digit Trip ID number which incremented each time the vehicle was started
- [SSS] is a 3-digit sequence number which started at 000 and incremented every 2 minutes
- [V] is a single character representing the vehicle on which the data is collected.
  - 's' is used for the silver car.
  - 'c' is used for the copper car.
- [F] is a single character representing the data file type
  - 'a' is used for C/ACC data
  - 'c' is used for communication from the lead vehicle data
  - 'd' is used for driver behavior and target data
  - 'f' represents the file containing the single video looking out of the front window
  - 'q' represents the file containing the four (quad) video images

- [EXT] is a 3-letter file extension, either .dat or .avi for data or video files, respectively

7.4.2 Common Data Collection Failures

There were typically between one to three data collection failures per participant, which resulted in the loss of all or partial data for an individual trip. Three modes of failure were common during the experiment. The first mode of failure happened only during the first six participants, after which the problem was identified and repaired. For the first six participants, there were a number of trips of both the copper and silver vehicles that were simply not recorded. This mode of failure was eventually traced to a routine in the DAS startup that was relying on updates from the GPS receiver before starting to record data. If the GPS did not start receiving current information shortly after the DAS was started (often due to clear sky issues, such as the vehicle being parked in an underground garage), then there was the potential for the DAS to become hung and to not record the subsequent trip. Failures of this type were discovered during the data download and validation stage by comparing the list of trips imported from the DAS to the hand-written driver log sheets.

A second mode of failure that was encountered involved a communication failure between two of the DAS system computers. In this mode of failure, the serial communication connection failed between the data recording computer and the computer that interfaces with both the vehicle's CAN data and the DSRC antenna. Although the DAS system still recorded some parameters for the entire trip, such as GPS and accelerometer, most vehicle data parameters, such as vehicle speed and cruise control settings, became frozen at the last value received just prior to the communication failure. This mode of failure generally occurred fairly early in the trip, so these trips were not included in subsequent analyses. Failures of this type were discovered by manually reviewing graphs of the data parameters during the initial data processing and coding step.

A third common mode of failure was characterized as a result of a DAS system reboot occurring during the middle of a trip. While the cause of the DAS system reboots is unknown, this mode of failure did not result in a total loss of trip data. This mode of failure typically resulted in the loss of 2 to 3 minutes of data while the DAS rebooted, but once the system finished rebooting, the recording of the data (.dat) files resumed. Unfortunately, after the reboot, the DAS system generally did not record video files. Failures of this type were generally discovered by manually reviewing the graphs of the data parameters during the initial data processing and coding step. Trips with system reboots were generally included in data analyses.

Other DAS failures occurred less frequently and were usually the result of isolated incidents in which data or video files for a particular trip were either missing or corrupted. As an example, video file corruption occurred on several trips taken by participant 10 which were later diagnosed as having occurred as a result of running low on disk drive space. Overall, the number of missing commute trips per driver was generally no more than one or two, and the impact of the data collection failures on the subsequent analyses should be minimal. All drivers had at least 10 ACC and 3 CACC commute trips that could be analyzed.

7.4.3 Initial Automated Data Processing

After a participant's data were downloaded from the vehicle, validated, and uploaded to a data repository, there were a number of initial data processing steps that needed to be performed.

The initial data processing was done using a script written for MatLab. This script basically ran through the data for each trip in order to summarize key parameters on both a trip-by-trip basis and on a participant-by-participant basis. On a trip-by-trip basis, the initial data processing script generated the following:

1. The initial data processing generated a best estimate synchronization between the DAS system clock and time as obtained by the GPS receiver on the vehicle. This synchronization was required in order to compare events that occurred in the lead vehicle with events that occurred in the following vehicle.
2. The initial data processing generated a number of indices, tables and calibration files which are used in later processing steps.
3. The initial data processing generated a .kml file which could be loaded into Google Earth allowing an analyst to visualize the trip's starting and ending points along with the route taken by the vehicle during the trip. (See Figure 7..)
4. The initial data processing generated graphs of key system and vehicle parameters as measured during the trip. (See Figure 7..)

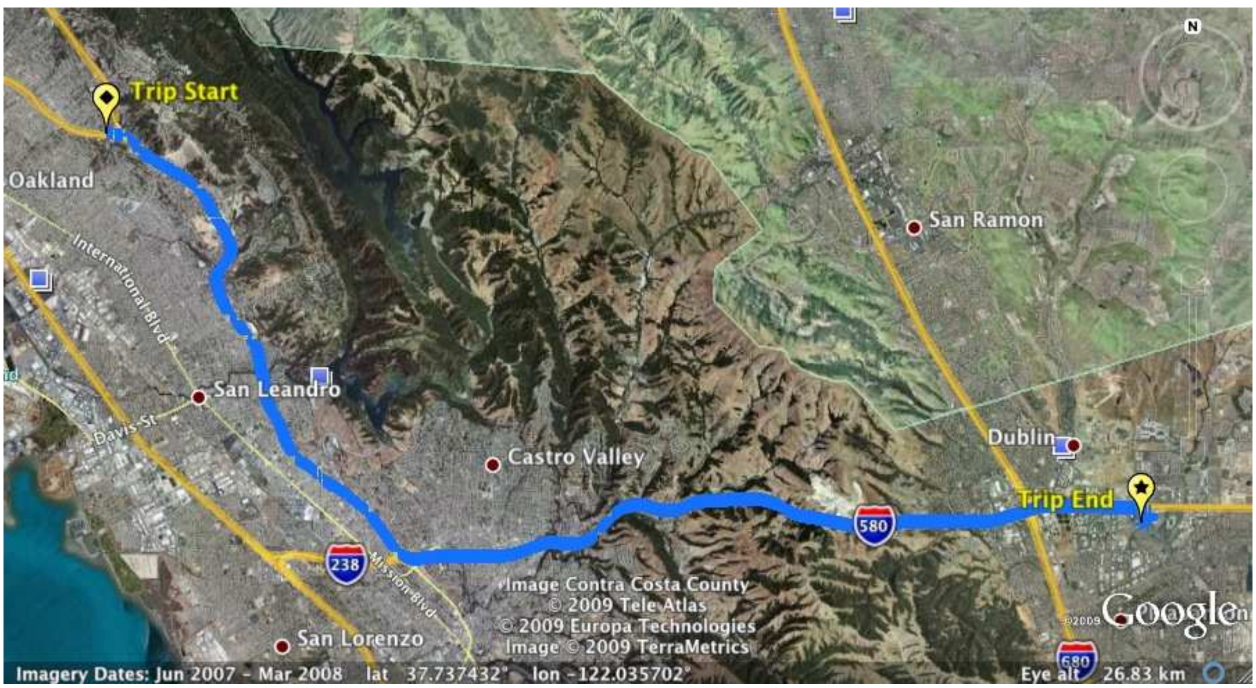

Figure 7.3: Google Earth Plot of a trip taken by a participant

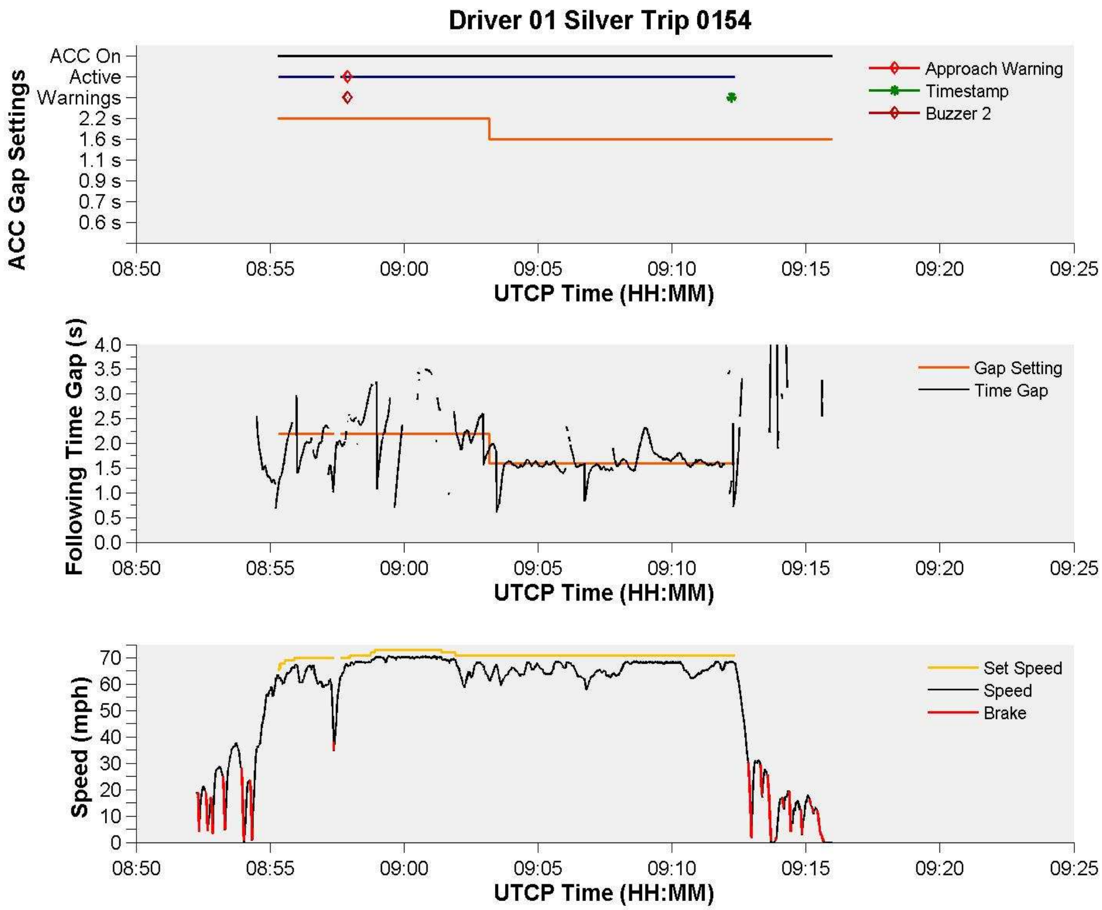

Figure 7.4: Plot of key vehicle and cruise control parameters for a trip.

On a participant-by-participant basis, the initial data processing script generated a trip summary dataset which listed all of the trips taken by a driver during the experiment. See

Table 7. for a description of the metrics that were generated for the initial trip summary data set. Although this data set was used to perform subsequent analyses, its immediate use was as a tool to help an analyst perform the manual trip coding task.

Table 7.6: Initial trip summary data set.

Parameter	Description
Driver ID Number	A random ID number assigned to each test participant
Vehicle Description	Silver (ACC Vehicle) or Copper (CACC Vehicle)
Trip ID Number	A vehicle-specific sequential trip number
Day/Month/Year	Trip Date
Clock Start/End	Original System Clock Times
UTC-P Start/End	Clock synchronized to UTC Pacific Time
Trip Length	Duration of Trip
ACC On Events	Number of times the ACC/CACC system was turned on
ACC On Time	Total length of time that the ACC/CACC system was on
ACC On Set Speed	Mean set speed when ACC system was on
ACC On Mean Speed	Mean vehicle speed when ACC system was on
ACC Active Events	Number of times that the ACC/CACC system was activated
ACC Active Time	Total length of time that the ACC/CACC system was active
ACC Active Set Speed	Mean ACC/CACC set speed when the system was active
ACC Active Mean Speed	Mean vehicle speed when the ACC/CACC system was active
Gap Setting Events	For each available gap setting, the number of times that the driver selected that gap setting
Gap Setting Times	For each available gap setting, the amount of time that the driver spent using that gap setting
Gap Setting Set Speeds	For each available gap setting, the mean set speed that the driver had set while using that gap setting
Gap Setting Mean Speeds	For each available gap setting, the mean vehicle speed that the driver was travelling while using that gap setting

7.4.4 Initial Manual Trip Coding

Once the initial automated data processing step was completed, an analyst was required to manually sort through each trip. The analyst was first looking for common DAS system failures, and second, coding each trip. The end result of the manual coding step was to create a list of trips and their characteristics which could then be used during the data reduction step as means to filter certain types of trips to be included or excluded from the subsequent analyses. Trips were coded along four dimensions as shown below:

1. Day of Week (e.g., Monday, Tuesday, etc.)
2. Day of Study (i.e., number of days since receiving the ACC vehicle)
3. Trip Purpose (Morning Commute, Evening Commute, or Other)
4. Trip Mode (Baseline, ACC, CACC, or Urban Driving)

The coding for the trip purpose separated out morning and evening commutes from other casual trips. This coding was done using both the time of the trip and the GPS traces recorded during the trip. Morning commute designated a trip from home to work, and evening commute designated a return trip from work to home. Since participants did not always go directly between home and work, there was some subjectivity regarding the coding of which trips were actually commutes, and occasionally, a commute may span multiple trips. However, the guiding principle for calling a trip a commute was whether or not the trip was made on roads that the participant frequently travelled between their home and their work. Thus, for all trips that were labeled as commutes, it can be assumed that the participant was highly familiar with the route.

The coding for trip mode allowed for four possibilities: baseline, ACC, CACC, or urban driving. Baseline trips were trips taken on designated baseline days where the participant was instructed not to use the ACC system. However, since the participants did not always follow the baseline day instructions, baseline day trips were manually verified to ensure that the participants did not use the ACC system during the trip before the trip was officially coded as a baseline trip. Trips coded as ACC indicated that the participant was free to use the ACC system during that trip, regardless of whether or not the participant actually chose to use the system. Trips coded as CACC trips indicated that the participant was driving the copper CACC-equipped vehicle, and trips coded as urban driving indicated that due to the trip's length and the roads being travelled during the trip, there simply was no opportunity for the participant to use either the ACC or CACC system.

7.4.5 Data Reduction

The final step of the data processing before the analysis phase is commonly referred to as the data reduction phase. The goal of the data reduction phase is to filter, combine, and process the system measurements, the vehicle measurements, and any other required observations into meaningful metrics that can be coded into a data set and subsequently analyzed. As an example, if one wanted to analyze the conditions when drivers activated the ACC system, the data reduction step would consist of the following steps:

1. Define the criteria that would constitute an ACC activation event. In this case, the criterion that defines an ACC activation even is already recorded in a single value that was recorded by the DAS.
2. Define a set of metrics of interest that would describe the event or the conditions around the event. In this case, the metrics may include vehicle speed and following distance at the time of the ACC system activation.
3. Locate all ACC activation events for all trips.
4. Process each ACC activation event, calculating and recording the selected metrics of interest for each event.

The majority of the data reduction was done using scripts written in MatLab that generated data sets for analysis. For each analysis discussed in the results chapter (Chapter 8), one or more scripts were written to process the raw system and vehicle data in order to create the appropriate metrics that were required for analysis. Manual checking of the video data was used clarify or code additional parameters or metrics as needed.

Chapter 7 Appendices:

Appendix XX
Adaptive Cruise Control Survey

The questions in this survey address your driving experience with the Adaptive Cruise Control (ACC) system. You will find three types of questions:

- Questions on a scale from 1 to 7, where you will indicate the side to which you feel closest by circling a number, for example:

  I liked driving this car.

  Strongly disagree 1 2 3 4 5 6 7 Strongly agree

  You would circle 7 if you strongly agree with the statement.

- Rank order items from 1 to 3, where the ranking is explained at the end of the question.

- Open ended questions, for which you will write answers.

Feel free to add comments around questions if you think it helps better express your opinion.

The information gathered through this questionnaire is confidential. The use of this information will respect your privacy and no names will ever be mentioned when using this data.

1 - Are you familiar with cruise control (speed only) systems?

☐ yes ☐ no

If yes, for approximately how long have you been using one? ________

Please rate your level of expertise

Novice 1 2 3 4 5 6 7 Expert

2 - Are you familiar with ACC systems?

☐ yes ☐ no

If yes, for approximately how long have you been using one? ________

Please rate your level of expertise

Novice 1 2 3 4 5 6 7 Expert

3 - Please describe the ACC system and how it works, in the way that you would describe it to another driver who has not yet seen or used the system.

4 - Overall, how comfortable did you feel driving the car using the ACC system?

Uncomfortable 1 2 3 4 5 6 7 Comfortable

5 - Do you think ACC is going to increase driving safety?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

6 - When using the ACC system in each of the following traffic conditions, did you follow other vehicles closer or further than you normally do?

Heavy traffic
Closer 1 2 3 4 5 6 7 Further

Moderate traffic
Closer 1 2 3 4 5 6 7 Further

Light traffic
Closer 1 2 3 4 5 6 7 Further

7 - In general, under which mode of operation did you feel like you reached your destination fastest? (Rank 1 fastest to 3 slowest)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

8 - How easy was it to drive using the ACC system?

Easy 1 2 3 4 5 6 7 Difficult

9 - Compare safety under these operation modes (from 1 most safe to 3 least safe)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

10 - Do you feel the following distance adjustment function is useful?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

11 - Were there times when the system became uncomfortable or inconvenient, causing you to manually disengage the system? (If so, please describe)

12 - What was your level of comfort for each of these gaps with the ACC?

Long gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Medium gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Short gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

13 - Under which mode of operation did you feel you reached your destination most safely? (from 1 most safely to 3 least safely)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

14 - How comfortable were you using the ACC system when driving in the following traffic environments?

Heavy traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Moderate traffic

Uncomfortable	1	2	3	4	5	6	7	Very comfortable

Light traffic

Uncomfortable	1	2	3	4	5	6	7	Very comfortable

15 - Which mode of operation (Manual, Conventional Cruise, ACC) required you to apply the brakes most often? (Rank 1 least braking to 3 most braking)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

16 - How long did it take you to be comfortable using the ACC system?

____

17 - When driving the ACC system, compared to manual driving, were you more or less aware of the actions of vehicles around you than you normally are?

Less aware	1	2	3	4	5	6	7	More aware

18 - How comfortable were you driving the ACC system in comparison to the manual driving?

Uncomfortable	1	2	3	4	5	6	7	More comfortable

19 - How frequently did you get into situations when you relied too heavily on the ACC to handle situations that it could not handle?

Frequently	1	2	3	4	5	6	7	Never

20 - When you were driving with the ACC, was your speed generally slower or faster than the speeds of neighboring vehicles?

Heavy traffic

Slower	1	2	3	4	5	6	7	Faster

Medium traffic

Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

21 - Did the system ever surprise you? (If so, please describe)

22 - How comfortable would you feel if your driving-age child, spouse, parents or other loved ones drove a vehicle equipped with ACC? (*Some of the cases may not apply to you; in this case, please mark the N/A box*)

Driving-age child (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Spouse (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Parents (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

23 - What did you think of the acceleration provided by the ACC system when pulling into an empty adjacent lane to pass other vehicles?

Too slow 1 2 3 4 5 6 7 Too fast

24 - What did you think of the deceleration rate provided by the ACC system when following a vehicle?

Too gentle 1 2 3 4 5 6 7 Too hard

25 - How much effort did it take to maintain a safe following distance when using each of the following modes of operation?

Manual driving (no ACC)
Difficult 1 2 3 4 5 6 7 Very easy

Cruise Control (speed control only)
Difficult 1 2 3 4 5 6 7 Very easy

Adaptive Cruise Control (speed and distance)
Difficult 1 2 3 4 5 6 7 Very easy

26 - How likely is it that you would have become more comfortable using the ACC system given more time?

Not likely 1 2 3 4 5 6 7 Very likely

27 - How comfortable were you using the ACC system on hilly roads?

Uncomfortable 1 2 3 4 5 6 7 Very comfortable

28 - How often, if ever, did you experience “unsafe” following distances when using the ACC system?

Frequently 1 2 3 4 5 6 7 Never

29 - Driving the ACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?

Less responsive 1 2 3 4 5 6 7 More responsive

30 - Compare (rank) these operation modes for comfort (from 1 most comfortable to 3 least comfortable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

31 - If you could add one feature to the system, what would it be and why?

32 - Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the ACC system as compared to driving under manual control?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

33 - Compare (rank) these operation modes for convenience (from 1 most convenient to 3 least convenient)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

34 - While using the ACC system, how often, if ever, did the system fail to detect a vehicle that you were approaching or following?

Often 1 2 3 4 5 6 7 Never

35 - As you got used to the ACC system, how would you rate the change of your level of confidence in the system? (circle 4 if your level of confidence remained the same)

More confident 1 2 3 4 5 6 7 Less confident

36 - Compare (rank) these operation modes for driving enjoyment (from 1 most enjoyable to 3 least enjoyable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

37 - How safe did you feel using the ACC system?

Not safe 1 2 3 4 5 6 7 Very safe

38 - If you could remove one feature/display method, what would it be and why?

39 - When using the ACC system, did you ever feel that you didn't understand what the system was doing, what was taking place, or how the ACC system might behave?

Very frequently 1 2 3 4 5 6 7 Very infrequently

40 - Would you rather have:

☐ An ACC ☐ a (speed only) cruise control ☐ no system

41 - In general, under which mode of operation did you feel like you reached your destination with the least stress related to driving? (Rank 1 least stress to 3 most stress)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

42 - While driving with the ACC, how confident did you feel about the system?

Very confident 1 2 3 4 5 6 7 Not confident

43 - Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

44 - Rank, in order of preference, the following modes of operation for personal use. (Rank 1 most desirable to 3 least desirable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

45 - When you were driving with the ACC, were you driving slower or faster than you normally drive?

Heavy traffic
Slower 1 2 3 4 5 6 7 Faster

Medium traffic
Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

Appendix XX

Cooperative Adaptive Cruise Control Survey

The questions in this survey address your driving experience with the Cooperative Adaptive Cruise Control (CACC) system. You will find three types of questions:

- Questions on a scale from 1 to 7, where you will indicate the side to which you feel closest by circling a number, for example:

  I liked driving this car.

  Strongly disagree 1 2 3 4 5 6 7 Strongly agree

  You would circle 7 if you strongly agree with the statement.

- Rank order items from 1 to 3, where the ranking is explained at the end of the question.

- Open ended questions, for which you will write answers.

Feel free to add comments around questions if you think it helps better express your opinion.

The information gathered through this questionnaire is confidential. The use of this information will respect your privacy and no names will ever be mentioned when using this data.

1 - Please describe the CACC system and how it works, in the way that you would describe it to another driver who has not yet seen or used the system.

2 - Overall, how comfortable did you feel driving the car using the CACC system?

Uncomfortable 1 2 3 4 5 6 7 Comfortable

3 - Do you think CACC is going to increase driving safety?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

4 - When using the CACC system in each of the following traffic conditions, did you follow the preceding vehicle closer or further than you normally do?

Heavy traffic

Closer 1 2 3 4 5 6 7 Further

Moderate traffic

Closer 1 2 3 4 5 6 7 Further

Light traffic

Closer 1 2 3 4 5 6 7 Further

5 - In general, under which mode of operation did you feel like you reached your destination fastest? (Rank 1 fastest to 4 slowest)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

6 - How easy was it to drive using the CACC system?

Easy 1 2 3 4 5 6 7 Difficult

7 - Compare safety under these operation modes (from 1 most safe to 4 least safe)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

8 - While driving with the CACC, how confident did you feel about the system?

Very confident 1 2 3 4 5 6 7 Not confident

9 - Under which mode of operation did you feel you reached your destination most safely? (from 1 most safely to 4 least safely)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

10 - Were there times when the system became uncomfortable or inconvenient, causing you to manually disengage the system? (If so, please describe)

11 - What was your level of comfort for each of these gaps with the CACC?

Long gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Medium gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Short gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

Shortest gap
Uncomfortable 1 2 3 4 5 6 7 Comfortable

12 - How comfortable were you using the CACC system when driving in the following traffic environments?

Heavy traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Moderate traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Light traffic
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

13 - Which mode of operation (Manual, Conventional Cruise Control, ACC, CACC) required you to apply the brakes most often? (Rank 1 least braking to 4 most braking)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

14 - How long did it take you to be comfortable using the CACC system?

____

15 - When driving the CACC system, compared to manual driving, were you more or less aware of the actions of vehicles around you than you normally are?

Less aware 1 2 3 4 5 6 7 More aware

16 - How comfortable were you driving the CACC system in comparison to the manual driving?

Uncomfortable 1 2 3 4 5 6 7 More comfortable

17 - When you were driving with the CACC, was your speed generally slower or faster than the speeds of neighboring vehicles?

Heavy traffic
Slower 1 2 3 4 5 6 7 Faster

Medium traffic
Slower 1 2 3 4 5 6 7 Faster

Light traffic
Slower 1 2 3 4 5 6 7 Faster

18 - How comfortable would you feel if your driving-age child, spouse, parents or other loved ones drove a vehicle equipped with CACC? *(Some of the cases may not apply to you; in this case, please mark the N/A box)*

Driving-age child (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Spouse (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Parents (☐ N/A)
Uncomfortable 1 2 3 4 5 6 7 Very comfortable

19 - Did the system ever surprise you? (If so, please describe)

20 - When driving the CACC system, compared to ACC driving, were you more or less aware of the actions of vehicles around you than you normally are?

Less aware 1 2 3 4 5 6 7 More aware

21 - How frequently did you get into situations when you relied too heavily on the CACC to handle situations that it could not handle? [SD or S]

Frequently 1 2 3 4 5 6 7 Never

22 - What did you think of the deceleration rate provided by the CACC system when following the lead vehicle?

Too gentle 1 2 3 4 5 6 7 Too hard

23 - How much effort did it take to maintain a safe following distance when using each of the following modes of operation?

Manual driving (no ACC)
Difficult 1 2 3 4 5 6 7 Very easy

Cruise Control (speed control only)
Difficult 1 2 3 4 5 6 7 Very easy

Adaptive Cruise Control (speed and distance)
Difficult 1 2 3 4 5 6 7 Very easy

Cooperative Adaptive Cruise Control (speed and shorter distance)
Difficult 1 2 3 4 5 6 7 Very easy

24 - How likely is it that you would have become more comfortable using the CACC system given more time?

Not likely 1 2 3 4 5 6 7 Very likely

25 - Compare (rank) these operation modes for convenience (from 1 most convenient to 4 least convenient)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

26 - Driving the CACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?

Less responsive 1 2 3 4 5 6 7 More responsive

27 - How comfortable were you using the CACC system on hilly roads?

Uncomfortable 1 2 3 4 5 6 7 Very comfortable

Between the ACC and CACC system, did you prefer one of the systems?

☐ yes ☐ no

If yes, which system and why?

28 - How often, if ever, did you experience "unsafe" following distances when using the **C**ACC system?

Frequently 1 2 3 4 5 6 7 Never

29 - Compare (rank) these operation modes for comfort (from 1 most comfortable to 4 least comfortable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

30 - Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the CACC system as compared to driving under manual control?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

31 - How comfortable were you driving the CACC system in comparison to the ACC driving?

Less comfortable 1 2 3 4 5 6 7 More comfortable

32 - If you could add one feature to the system, what would it be and why?

33 - As you got used to the CACC system, how would you rate the change of your level of confidence in the system? (circle 4 if your level of confidence remained the same)

More confident 1 2 3 4 5 6 7 Less confident

34 - How likely is it that you would have become more comfortable using the CACC system if you could have used it to follow any vehicle?

Not likely 1 2 3 4 5 6 7 Very likely

35 - Compare (rank) these operation modes for driving enjoyment (from 1 most enjoyable to 4 least enjoyable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (Speed and distance)

__ Cooperative Adaptive Cruise Control (Speed and shorter distance)

36 - How safe did you feel using the CACC system?

Not safe 1 2 3 4 5 6 7 Very safe

37 - Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the CACC system as compared to driving with the ACC system?

More comfortable 1 2 3 4 5 6 7 Less comfortable

38 - When using the CACC system, did you ever feel that you didn’t understand what the system was doing, what was taking place, or how the CACC system might behave?

Very frequently 1 2 3 4 5 6 7 Very infrequently

39 - Would you rather have:

☐ An ACC ☐ a cruise control ☐ no system ☐ A CACC

40 - Driving the CACC system, compared to driving the ACC system, did you find yourself more or less responsive to actions of vehicles around you?

Less responsive 1 2 3 4 5 6 7 More responsive

41 - If you could remove one feature/display method, what would it be and why?

42 - In general, under which mode of operation did you feel like you reached your destination with the least stress related to driving? (Rank 1 least stress to 4 most stress)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shorter distance)

43 - Do you feel the following distance adjustment function is useful?

Strongly disagree 1 2 3 4 5 6 7 Strongly agree

44 - How likely is it that you would have become more comfortable using the CACC if you could have set your own speed?

Not likely 1 2 3 4 5 6 7 Very likely

45 - Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

46 - Rank, in order of preference, the following modes of operation for personal use. (Rank 1 most desirable to 4 least desirable)

__ Manual driving (no ACC)

__ Cruise Control (speed only)

__ Adaptive Cruise Control (speed and distance)

__ Cooperative Adaptive Cruise Control (speed and shortest distance)

47 - When you were driving with the CACC, were you driving slower or faster than you normally drive?

Heavy traffic

Slower 1 2 3 4 5 6 7 Faster

Medium traffic

Slower 1 2 3 4 5 6 7 Faster

Light traffic

Slower 1 2 3 4 5 6 7 Faster

Chapter 8: Results on Driver Usage of ACC and CACC

The results presented and discussed in this Chapter summarize data at the trip level and within the trip for the first 12 participants of the study. The contents of the data set are summarized in the table below.

Table 8.1: Description of data set per data collection condition

	Baseline	ACC	CACC
Number of trips	29	142	52
Number of events	412 following events	540 single activations	352 single activations

Based on the experimental plan, there should have been 48 baseline trips (4 per participants), 120 ACC trips (10 per participants) and 48 CACC trips (4 per participants). The difference between the expected and actual number of trips can be explained by data loss on some of the trips as well as instruction misunderstanding on the part of participants, especially for the baseline and ACC conditions. As there was no experimenter present in the vehicle to remind them, some of the participants did not complete all of the baseline commutes.

8.1 Baseline following events behavior without ACC

A following event was defined as any event with a detected target that lasted more than five seconds. In order to account for target drops, events with a front target separated by less than 2 seconds were merged. Although these events have been termed following events, the data was not further reduced in order to determine whether the driver was actively following the lead vehicle, i.e., adapted the vehicle's speed to the speed of the front vehicle. The two dimensions that are presented for describing the following events are their duration and the time-gap series that can be plotted.

The event duration is first presented based on the number of trips and for each driver, as the number of trips varied per driver.

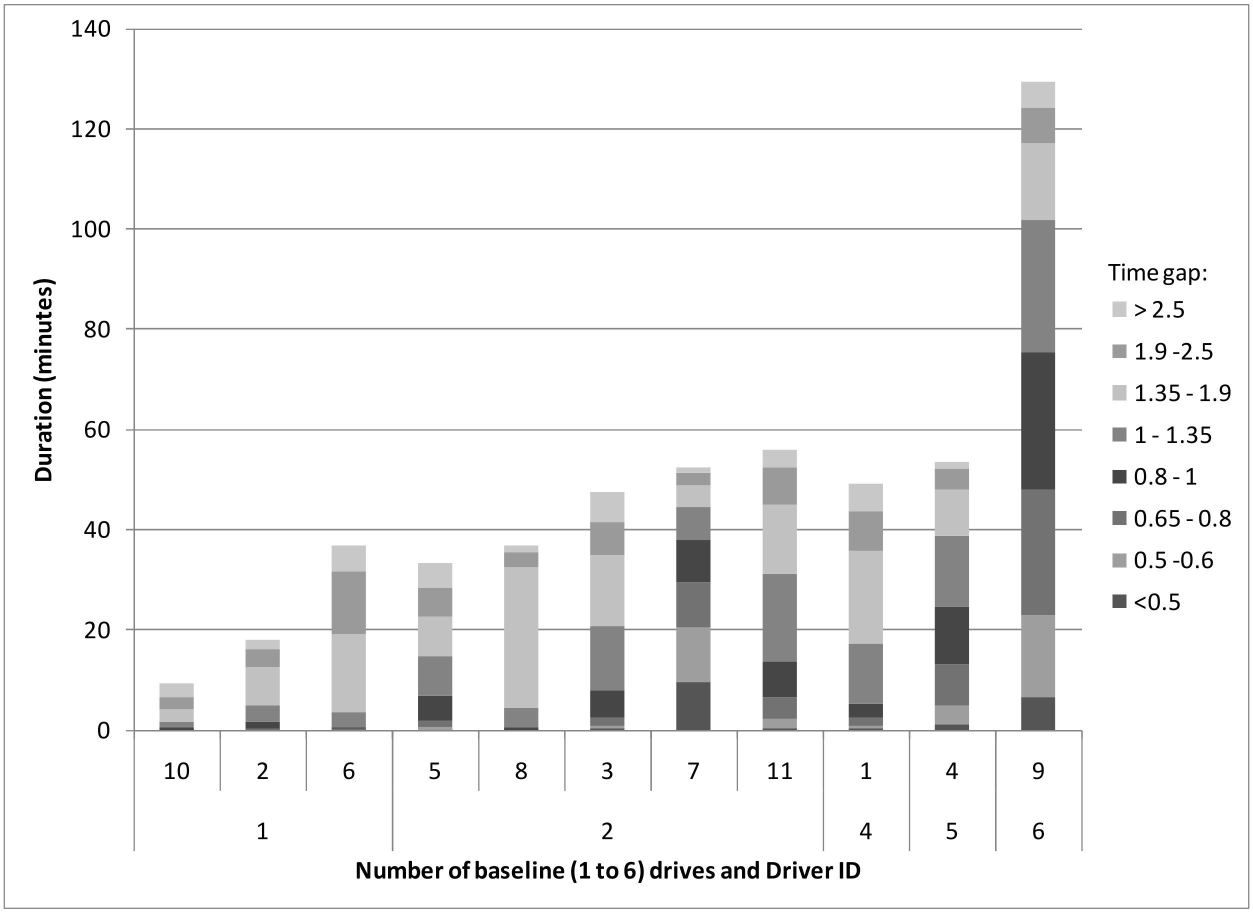

Figure 8.1: Baseline drive following event durations in each time gap range by driver

In Figure 8-1 above, the x axis contains two levels of information. At the lowest level is the number of baseline drives that were recorded, at the higher level is the Driver ID. For example, Driver 10 had 1 baseline trip recorded, while Driver 1 had 4 baseline drives recorded. As can be seen in Figure 8-1, data for two baseline trips have been recorded for almost half the sample. The grand total of following time ranges from approximately 10 minutes (Driver 10) to over 2 hours (Driver 9).

The other level of information displayed in Figure 8-1 is the proportion of time drivers have spent at specific time gaps. In order to represent it, the data have also been sorted based on the following eight time gap categories:

- <0.5 sec.
- 0.5 to 0.6 sec
- 0.65 to 0.8 sec
- 0.8 to 1 sec
- 1 to 1.35 sec
- 1.35 to 1.9 sec
- 1.9 to 2.5 sec
- > 2.5 sec

This sorting reveals the proportion of the following events conducted within these time-gap categories and the variations among drivers. For example, most of the following events recorded for Driver 8 were conducted within the 1.35 to 1.9 sec. time gap category, while for Driver 7 most of the following events were conducted within and under the 0.8 to 1 sec. time-gap category.

Another element that was investigated was the duration of the individual following events across all drivers. The average length for the following events was 1.27 minutes (Standard deviation: 0.12), with a minimum of 0.1 minute and a maximum of 21.7 minutes. The data set has been sorted in time bins based on the length of the event. The first two bins cover events that lasted half a minute, 0 to 30 sec. and 30 sec. to 1 min. respectively, and the rest of the bins cover periods of time incremented by 1 min. It is likely that events lasting less than 30 sec. were vehicles moving in and out of lanes and although they may have required a response from the driver, it is unlikely that the driver engaged in a regulation of the gap with the front vehicle. The distribution of the following events per length of time categories is illustrated in Figure 8-2.

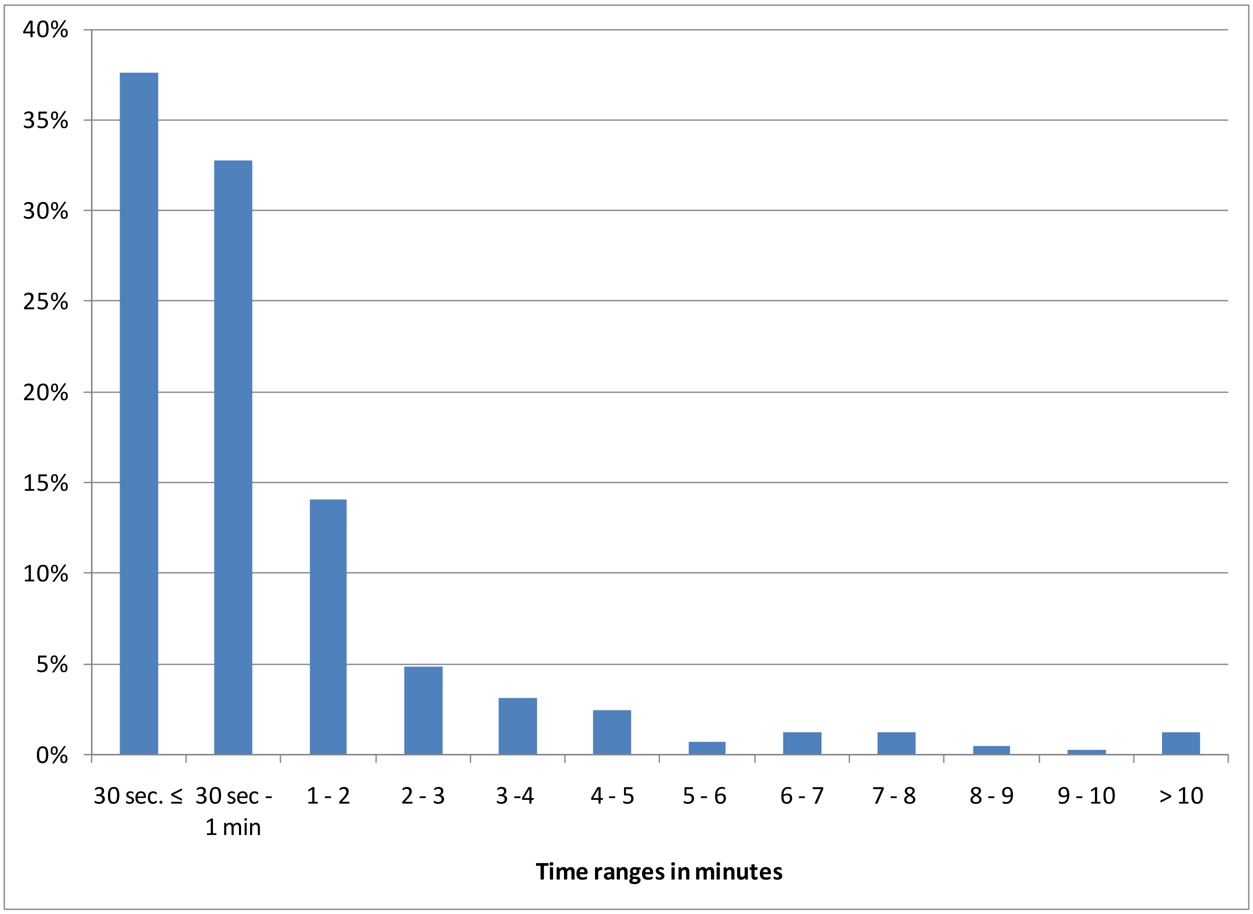

Figure 8.2: Distribution of following events by duration

Over 60% of the following events lasted less than a minute. Further data analysis will concentrate on the starting and ending conditions of the following events (e.g. whether the Subject Vehicle (SV) catches up with the lead vehicle or the lead vehicle moves in front of the

SV), the amount of time between following events and whether the driver was "actively" engaged in regulating the gap with the lead vehicle, either by accelerating or slowing down.

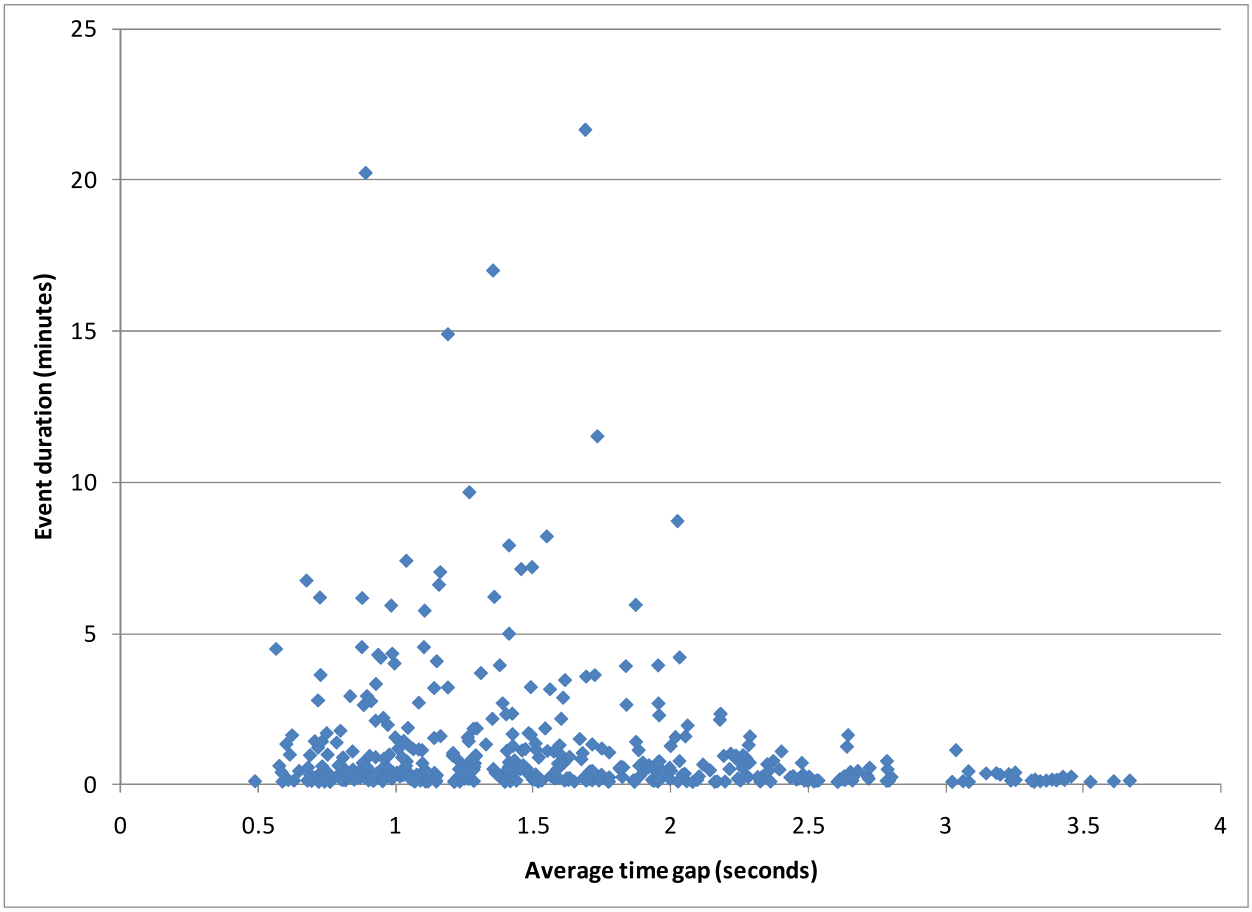

Figure 8.3: Average time gap vs. event duration

In Figure 8-3, the average time gap for a following event is displayed on the x axis, and the event duration is displayed on the y axis. It can be seen that the following events that lasted more than 1 minute had average time gap less than 2.25 seconds and that the events lasting more than 5 minutes had an average time gap shorter than 2 seconds. An explanation for this relationship between the average time gap and event duration is that in heavier traffic, the drivers have to follow other vehicles for a longer period of time and at closer range, while when traffic is lighter, there is more freedom for a driver to maintain a desired speed and not follow other vehicles at a close range. To verify this explanation will require further analysis of the following events and a categorization of the surrounding traffic density.

The other dimension considered for the analysis of the baseline data was the time gap range at which the drivers followed. This information is displayed in Figure 8-4, with a cumulative distribution of the amount of time spent at time gaps ranging from less than half a second to over 2.5 seconds.

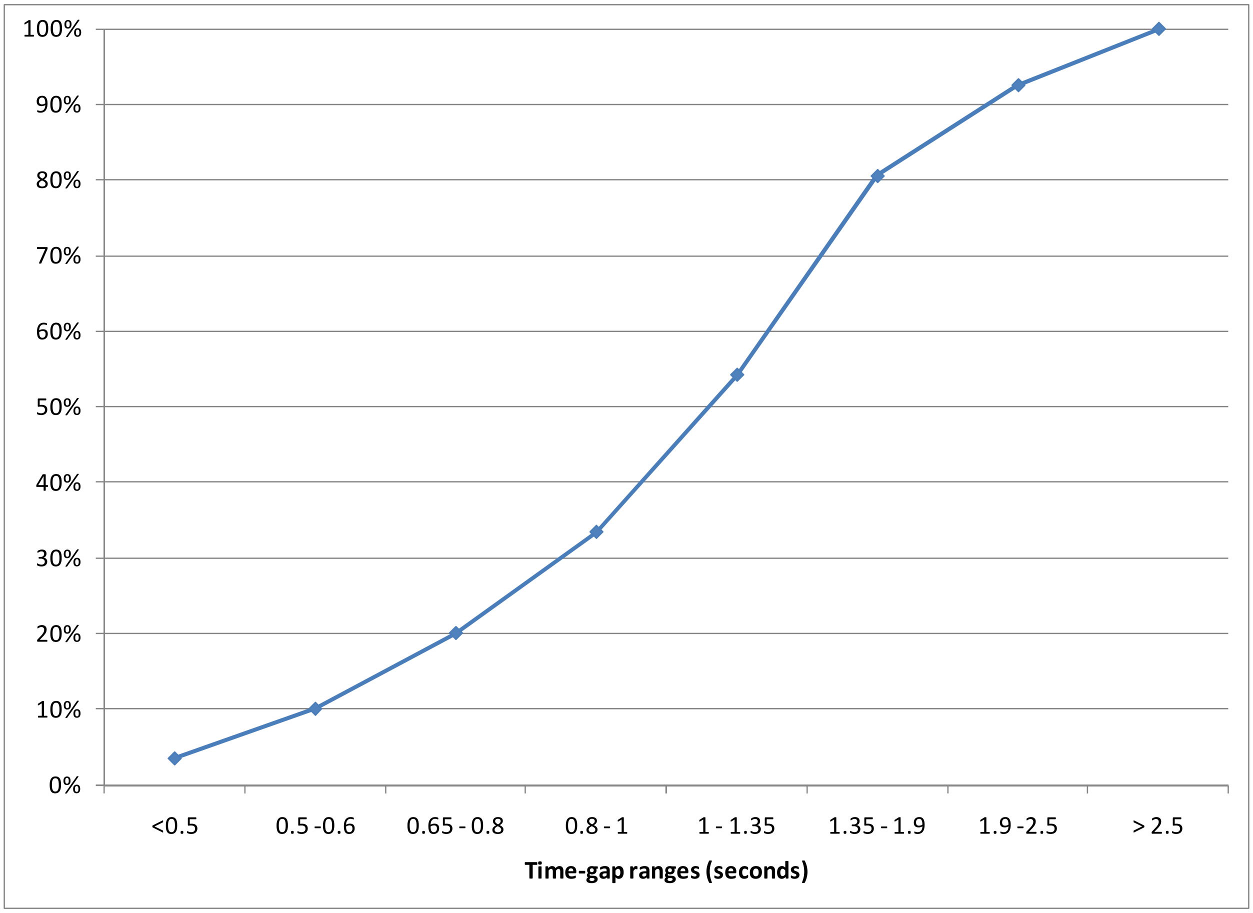

Figure 8.4: Cumulative distribution of the amount of time spent within time gap ranges

The 50th percentile of the time gap is in the 1 to 1.35 seconds category.

8.2 Highway driving behavior with ACC

The description of the highway driving with ACC is defined at three levels. At a high level description, the duration of ACC usage will be described. Then the conditions for activating and deactivating the system will be presented in terms of speed and gap setting selection. Finally, distributions of the time-gap settings within the activations will be presented.

8.2.1 Duration of ACC usage

In order to present the duration of the ACC activations, the data set has been sorted in 12 categories, where the first 2 categories represent a half minute each and the next categories are incremented by one minute.

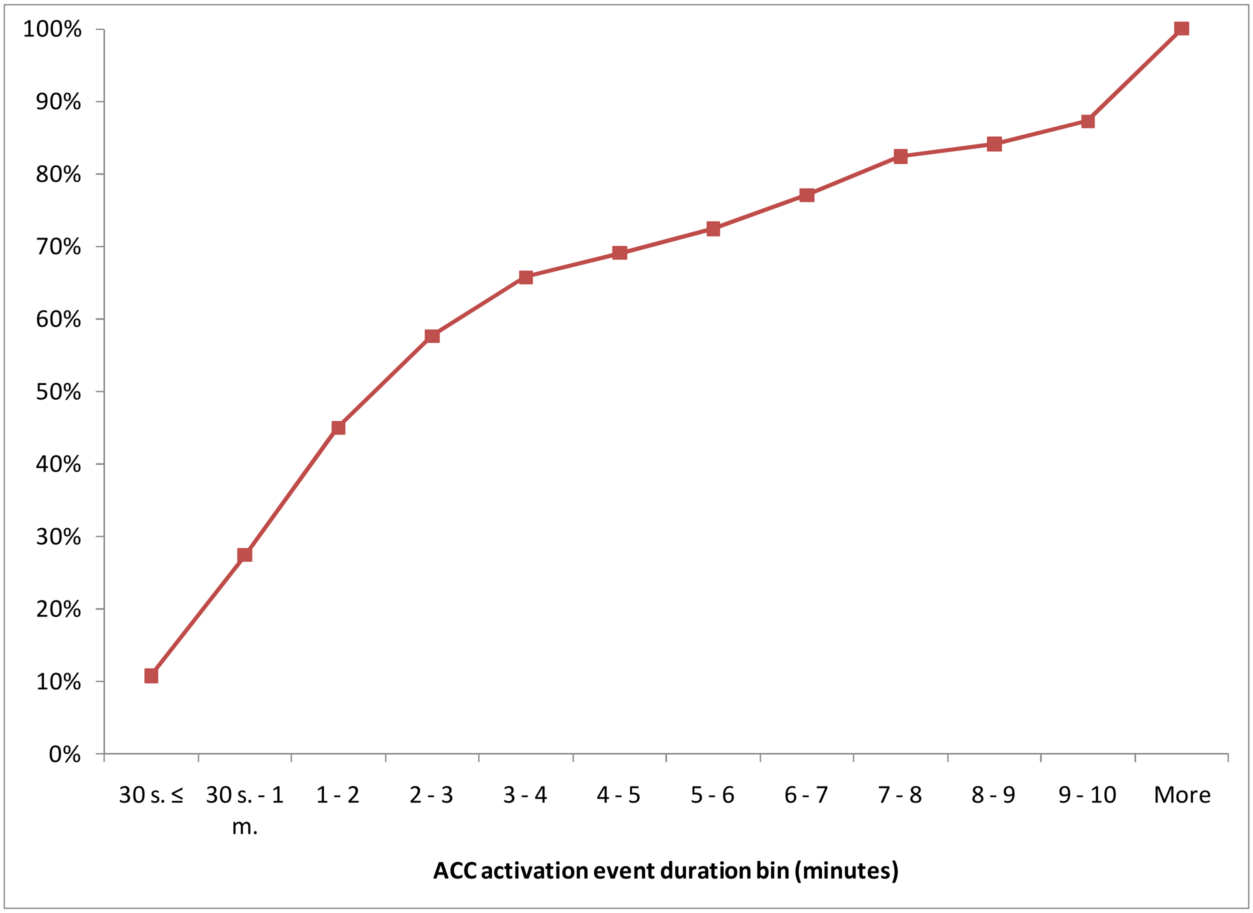

Figure 8.5: Cumulative distribution of ACC event duration

Figure 8-5 displays the cumulative distribution of the ACC activation duration. The distribution flattens at the category of events lasting between 4 and 5 minutes. The average activation duration is 4.25 min (standard deviation 4.8), with a minimum of 0.2 min and a maximum of 31 minutes.

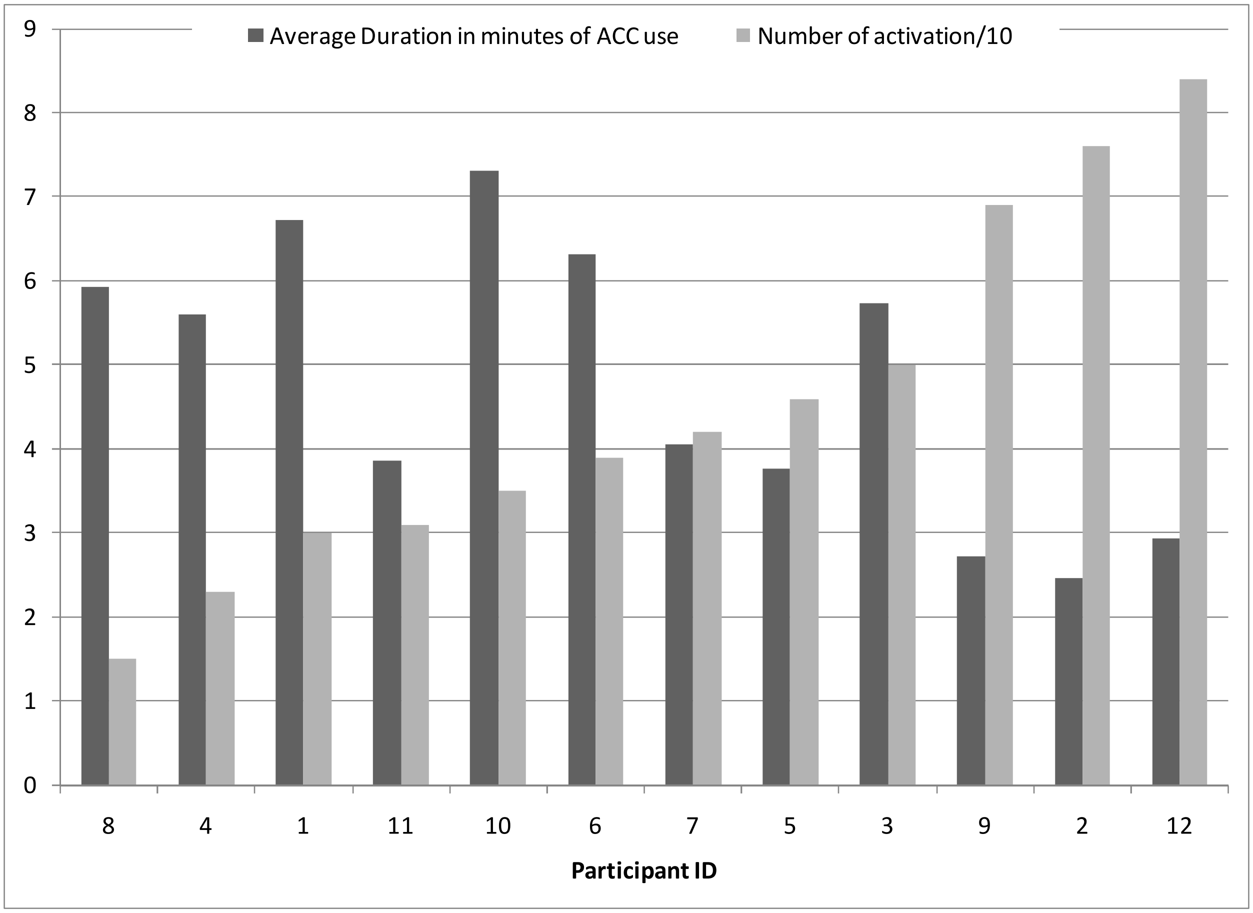

Figure 8.6: Average duration of each ACC use and number of individual activations

Figure 8-6 displays the average event duration as well as the total number of activations per driver. The number of activations has been divided by 10 in order to facilitate the reading of the plot. The plot has also been ordered based on the number of activations. For example, the participant for whom the smallest number of single activations has been recorded is participant 8, while the participant for whom the largest number of single activations has been recorded is driver 12. This ordering shows that the larger number of activations is associated with a lower average duration of each activation. In other words, the participants who have a lower number of activations tend to have longer average activations. A possible explanation is that these drivers had commutes on less congested areas than drivers with a higher number of activations, and they were less likely to turn off the system due to traffic. This explanation will have to be validated in subsequent analysis with a characterization of the level of traffic faced by the participants on their commutes.

8.2.2 Activation and deactivation conditions

The activation and deactivation elements that are presented and discussed below are extracted from the recorded time history data set, and give a picture of when the system was engaged, what were the parameters set at, i.e., what was the current speed, the set speed, the gap setting, was a lead vehicle present, and if so, what was the gap between the two vehicles relative to the gap setting? From this perspective, for each of the activations within a trip a new data set was created. Figure 8-7 presents the points that were extracted

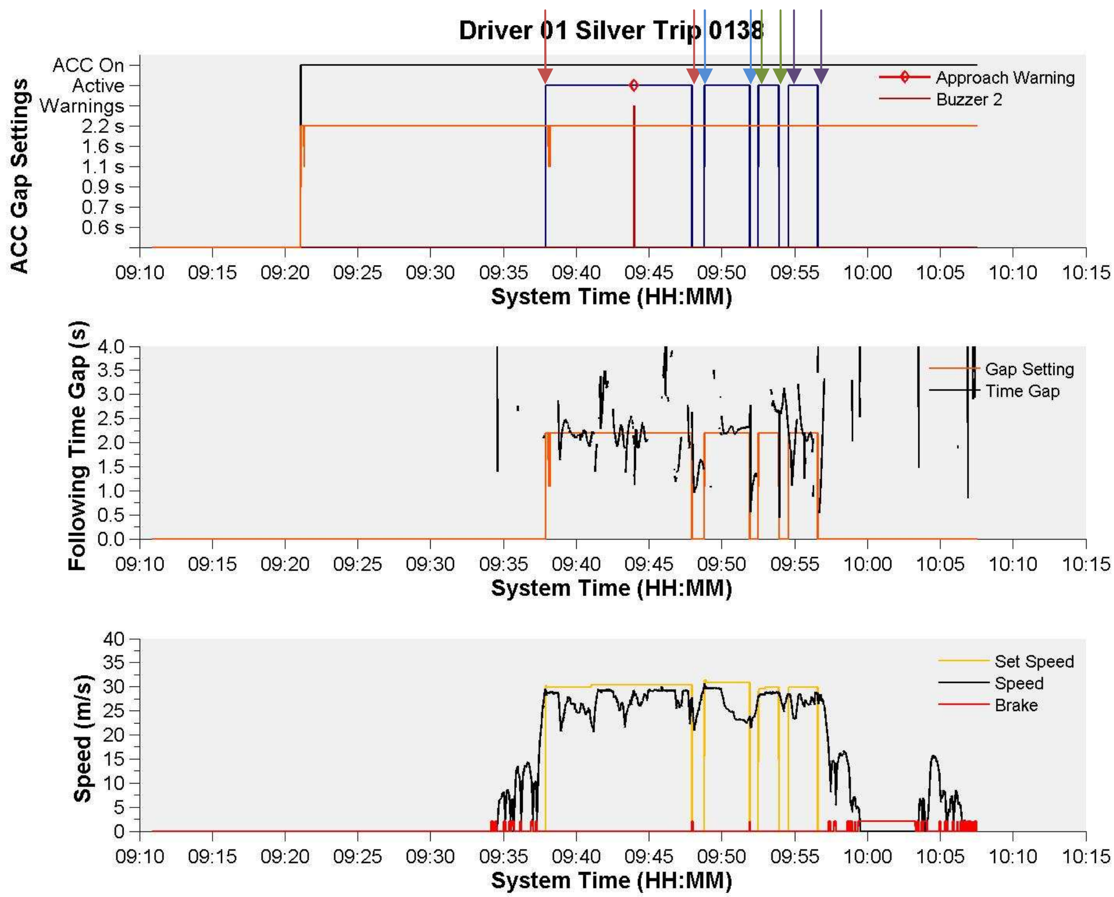

Figure 8.7: Extraction of information about beginning and end of system activations

For the trip depicted in Figure 8-7, there were four activations of the system; information was extracted from the data files in order to specify, for each activation and deactivation, what were the systems' settings in terms of gap and speed, the actual gap and speed. We first present data relative to the speed control and then to the gap control.

8.2.1.1 Speed control

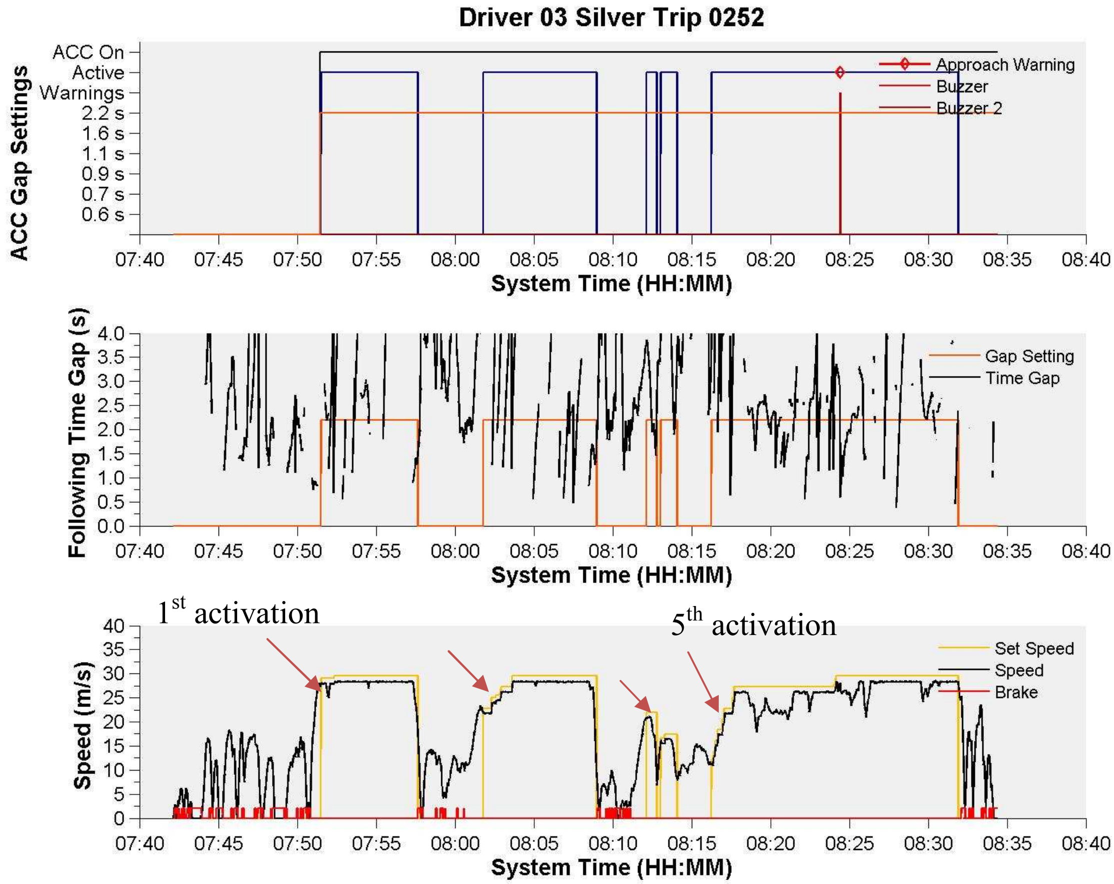

Figure 8.8: Extracting pattern for system engagement

In Figure 8-8 (3rd graph, speed vs. time), we can distinguish two cases for speed setting:

a) cases where the driver reaches the cruising speed manually prior to engaging the system, and the set speed will be close enough to the desired speed and lead to few adjustments (1st activation) and

b) cases where the set speed will be actively increased by the driver via the system speed button control, such as the second and fifth activation.

What we do not see in this case is the use of the resume function of the system.

This procedure for reaching desired speed manually can be an artifact of how drivers enter their desired speed. For the first activation, they always have to use the set speed function[2], but for any subsequent activation, they have the choice between the set speed or resume function. For this case, the driver uses the set speed function for each activation, while the desired cruising speed seems to be the same for each "long" activation. A possible way to

[2] As a reminder, a driver can set the speed based on the actual vehicle speed, or, after the first activation, use the resume speed function to reinstate the speed that was first set.

determine which function was used for the speed setting is to plot the set speed when the system was engaged vs. the actual speed, as was done in Figure 8-9.

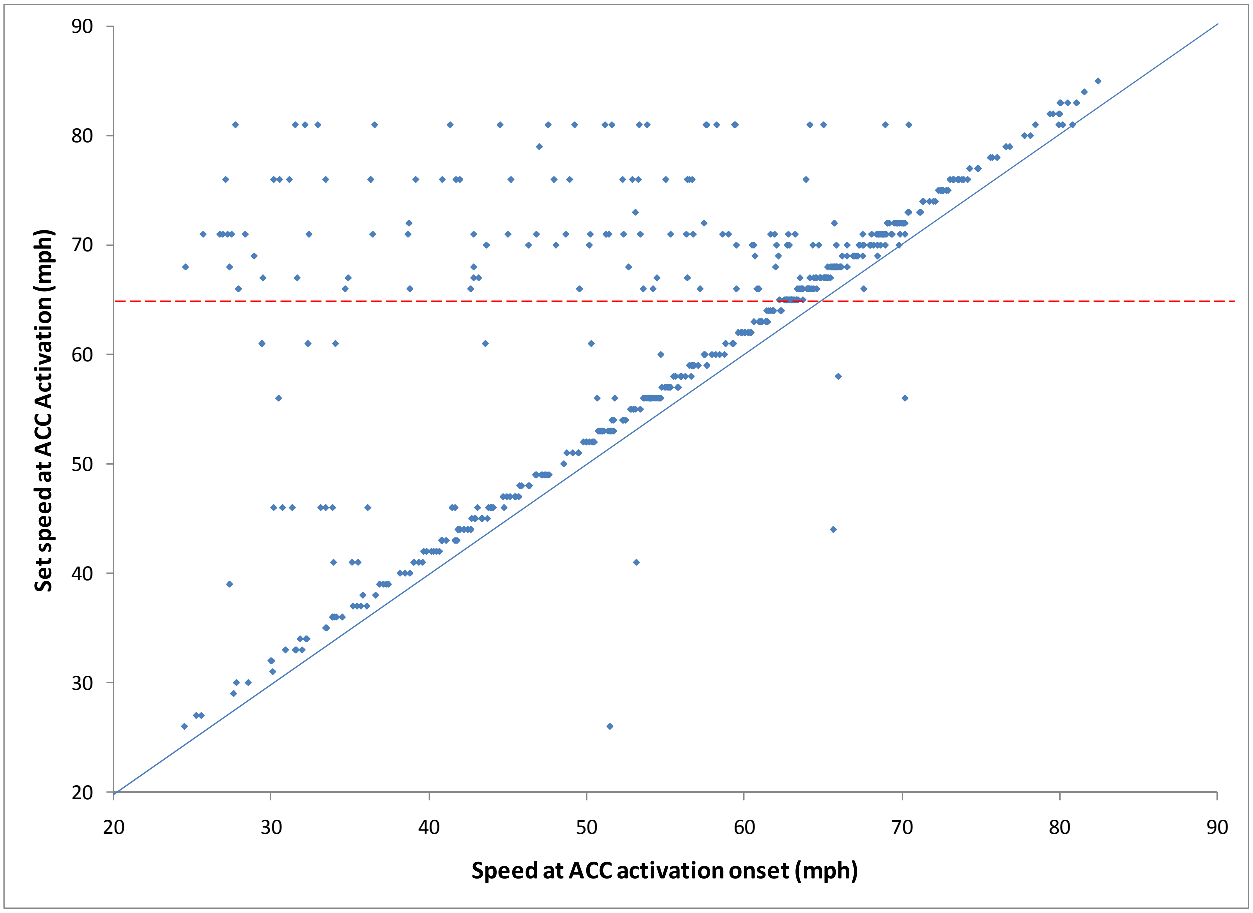

Figure 8.9: Actual speed at ACC system activation onset vs set speed

Two patterns can be distinguished in Figure 8-9:

Pattern 1: the set speed and the actual speed are within 3 mph of each other. This pattern is represented by the points that follow the solid line (over 70% of the cases).

Pattern 2: the set speed is higher than the actual speed when the system is engaged, and is visible in Figure 8-9 by the points that are on the top left side of the figure. It is interesting to note that most of these points are also above the 65 mph limit (dotted line), which indicates that the drivers used the resume function even though there was a large difference between the set and actual speed (see for example the points where the actual speed is within 30 to 40 mph and the set speed is within 70 to 80 mph).

A few odd points can be seen on the right side of the line, where the set speed is lower than the actual speed. These cases have not been analyzed as of the writing of this report. Further analysis will also address the speed at which the drivers settled for subsequent activations (such as activation 3 or 5 as shown on Figure 8-8) relative to the previous activation. The overwhelming use of the set speed function over the resume speed function is interesting in the sense that the workload for resuming the desired speed is lower than the workload for setting and adjusting the speed.

A similar plot, Figure 8-10, describes the conditions at system deactivation.

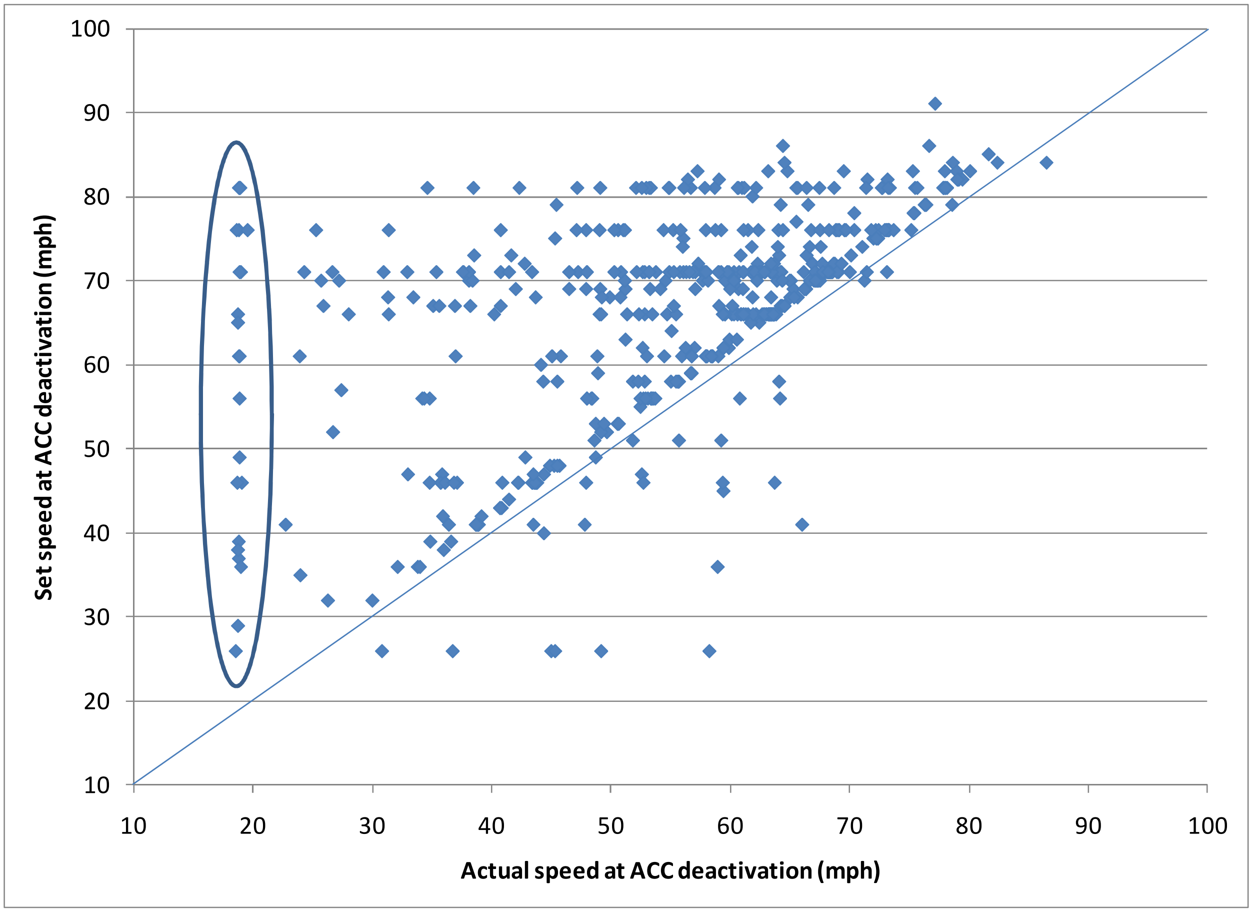

Figure 8.10: Actual speed at ACC system deactivation vs set speed

Three patterns can be identified in Figure 8-10. For a few instances, the system was automatically shut off when the vehicle speed fell to 20 mph (circled cases on the left of the graph). The second pattern indicates cases where the set speed and the actual speed were within 3 mph of each other. These cases can be seen along the solid line and represent a little less than half of the total cases, at 45% of the sample. The last pattern is represented by the cases between the line and the circle, and for which the actual speed was lower than the set speed.

8.2.1.2 Time gap setting choices

The time gap setting choices are described in terms of settings selected at the beginning and end of each activation, as well as the presence of a lead vehicle for these conditions and the size of the actual gap vs. the selected gap.

In order to describe the gap setting choices, the data have been sorted by activation order in the trip. Figure 8-11 illustrates the number of trips with each number of activations per trip. For example, for 27 trips there was only one activation of the system recorded, and for 6 trips there were 9 activations recorded.

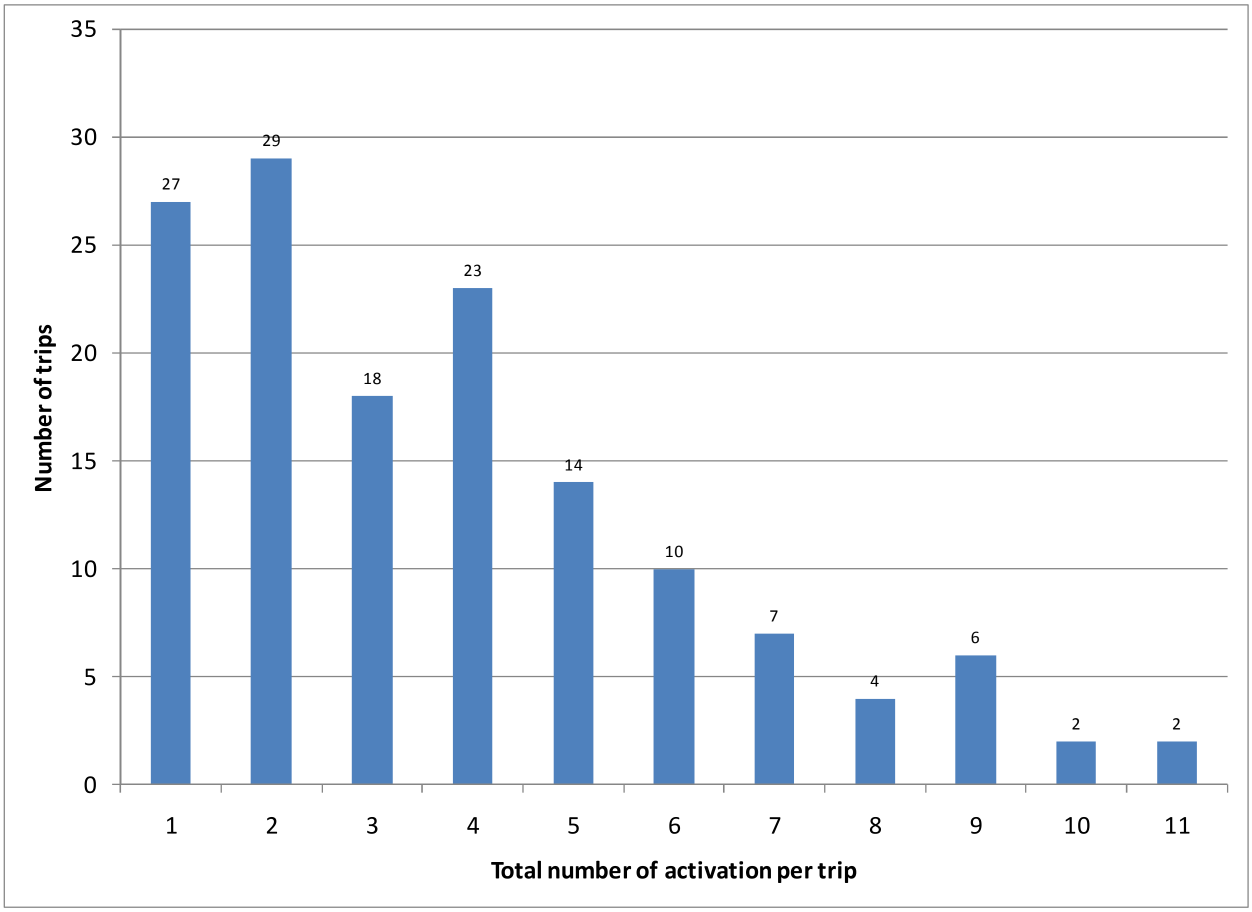

Figure 8.11: Number of trips with each number of activations per trip

The 75th percentile of the distribution is at 5 activations; hence we decided to focus the choice settings on the first five activations per trip individually and collapse the rest of the activations into one category called 'More' in the figures below. Figure 8-12 displays the proportion of cases for each selected gap setting for the first 5 activations.

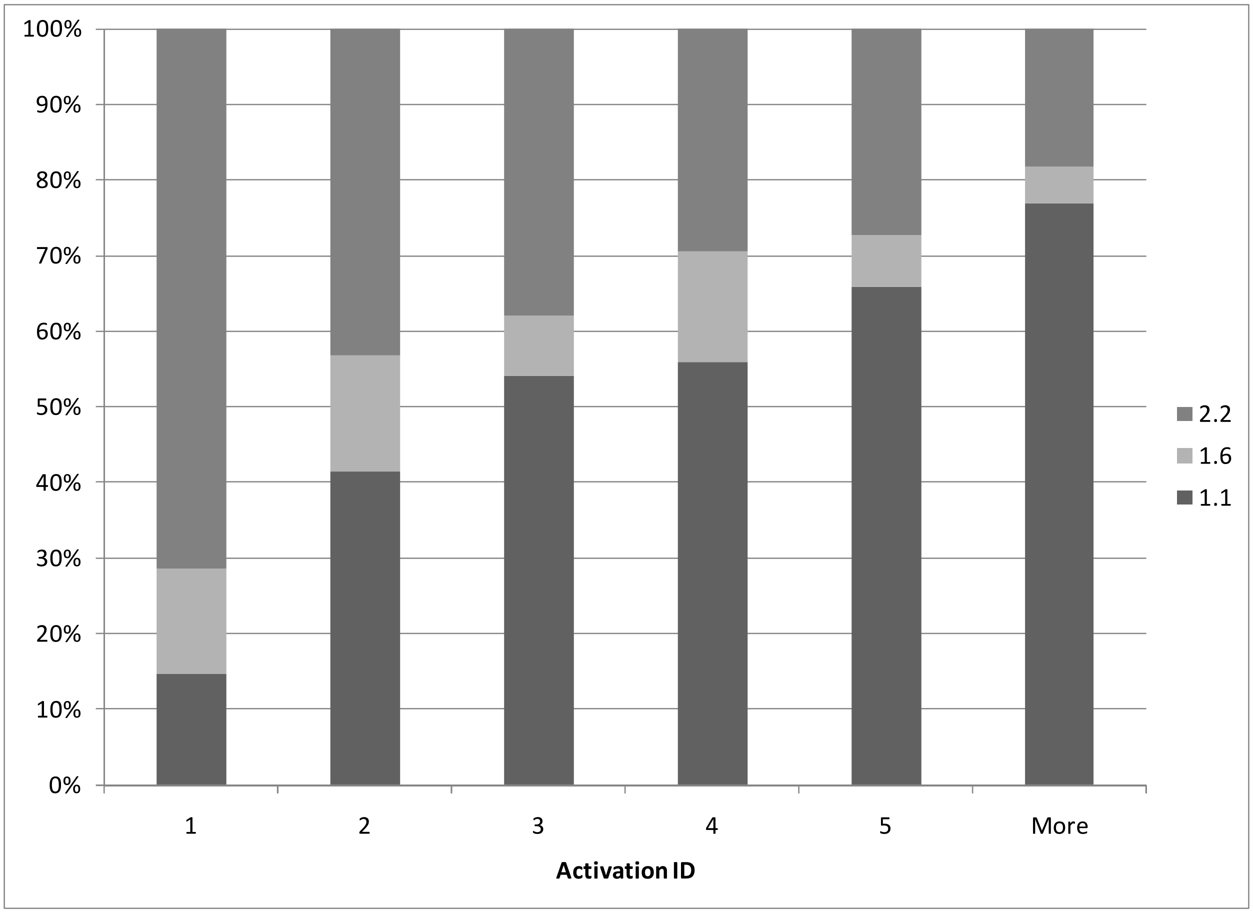

Figure 8.12: Distribution of time gap setting at activation onset by activation number

The distribution shows that the 2.2 sec time gap setting was selected in more than 70% of the cases for the first activation and that as the number of activation within a trip increases, so does the representation of the 1.1 sec. time gap setting. The 1.6 sec. time gap setting represents 10 to 15 % of the choices for the first 4 activation, and its ratio diminishes as the number of activation increases. The over representation of the longest gap setting at the first activation illustrates that the driver was given the default setting when turning the system on.
.

The other aspect that was investigated in terms of gap selection at the activation of the system was the presence of a lead vehicle and, for the relevant cases, the size of the actual gap vs. the selected gap. The size of the actual gap can be shorter, identical or longer than the one that the system will regulate. In order to analyze this relationship, the actual gaps had to be sorted relative to each of the gap settings. For example, an actual time gap of 1.2 will be sorted into the identical gap range for the gap setting of 1.1, while it will be in the shorter gap range category for a system setting of 1.6. Table 8-2 describes the limits of the bins for the actual gaps relative to the selected gap for the ACC system.

Table 8.1: Categorization of actual gaps relative to gap settings - ACC system

ACC Gap setting	Classification based on range of actual gaps measured		
	Shorter gap range	Identical gap range	Longer gap range
1.1	0.2 to 0.9	0.91 to 1.3	>1.31
1.6	0.2 to 1.4	1.41 to 1.8	>1.81
2.2	0.2 to 2	2.1 to 2.4	>2.41

The sorted data are plotted in histogram form in Figure 8-13.

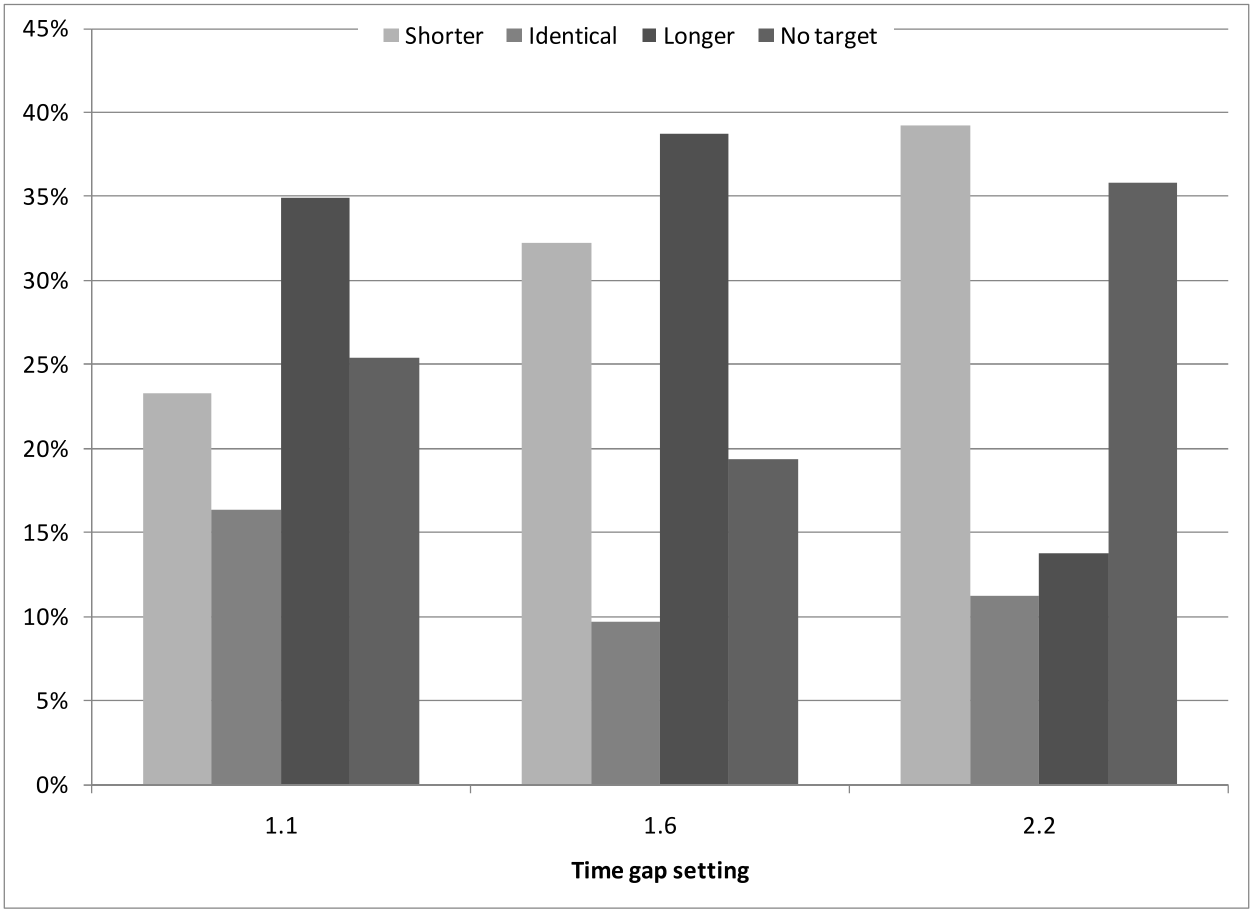

Figure 8.13: Distribution of actual gap size relative to gap setting at ACC activation

Figure 8-13 supports the analysis of the following situation when the drivers decided to engage the system. In terms of presence of a lead vehicle, for all gap settings there was a fair amount of system activation that occurred when no target was in range of the system, from 20% for the 1.6 sec time gap setting to 35% for the 2.2 sec time gap setting. This last time gap setting could have had more cases without a target because of its over-representation in the first activation of the system. Further analysis will integrate how long after entering the highway the system was engaged. For example, drivers could have engaged the system for the first time immediately upon entering the highway.

For cases when a lead vehicle was present, for the 1.1 and 1.6 sec. time gap settings, the greater part of the activations occurred when the gap with respect to the lead vehicle was longer than the gap that will be regulated by the system (35%), with the second biggest category being a shorter gap. For the 2.2 sec setting, for the greater number of cases the system was engaged when the actual gap was shorter than the gap that would be regulated.

The same parameters were used for describing the deactivation conditions.

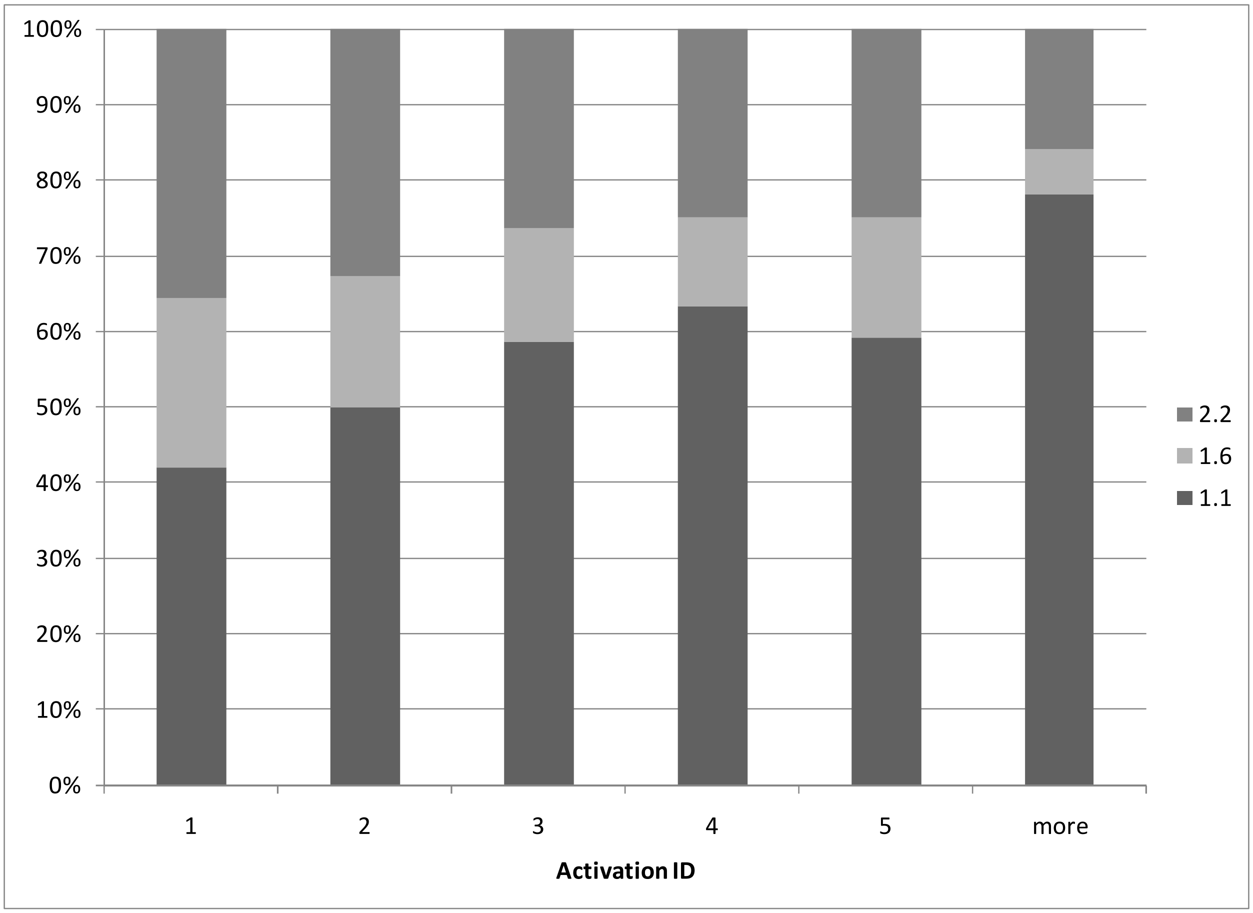

Figure 8.14: Distribution of time gap setting at deactivation per activation number

In Figure 8-14, the distributions of the gap settings at deactivation per activation occurrence follows a similar pattern as at the activation. However, it is interesting to note that while 25% of the first activations started with a time-gap setting of 1.1 sec, 40% of the first activations terminated with a time-gap setting of 1.1 sec, which is indicative of a setting change during the activation.

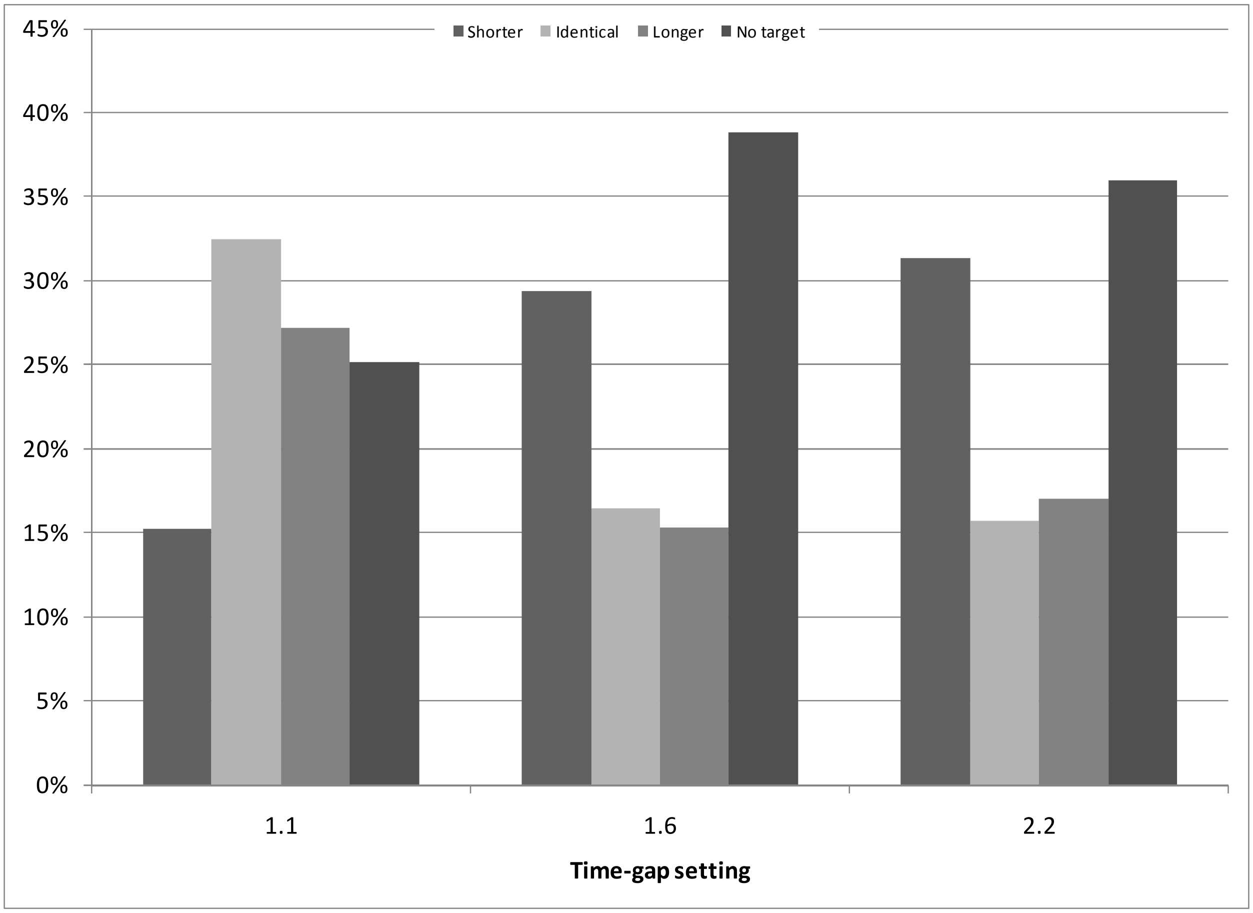

Figure 8.15: Distribution of gap size relative to gap setting at ACC deactivation

In Figure 8-15, the distribution of cases among the different categories is similar for the 1.6 and 2.2 sec time gap settings, where there was no target in range when the system was deactivated for over a third of the cases. When looking at cases where a target was present, the actual gap being shorter than the set gap represents the majority of the cases, which could be indicative of a decision to deactivate the system due to a cut-in at a shorter gap than the one regulated by the system. Further steps are required to verify this assumption, such as identifying vehicle cut-ins from other lanes, as well as lane changes by the SV. The pattern seems to be different at the shortest gap setting, as for this case the trend seems to indicate that the system was deactivated either when regulating the gap or when the actual gap was bigger. For this case, there was also a fair amount (25%) of deactivation when no target was in range of the sensors. A further step in the data analysis for cases when the system is deactivated when no target is present will be to identify the last deactivation of a trip and its location (highway vs. off-ramp), in order to account for deactivations when leaving the highway.

8.2.2 Description of gap setting usage within ACC activations

Gap setting usage is presented in terms of distribution across all the drivers, based on the occurrence of the commute, and per driver.

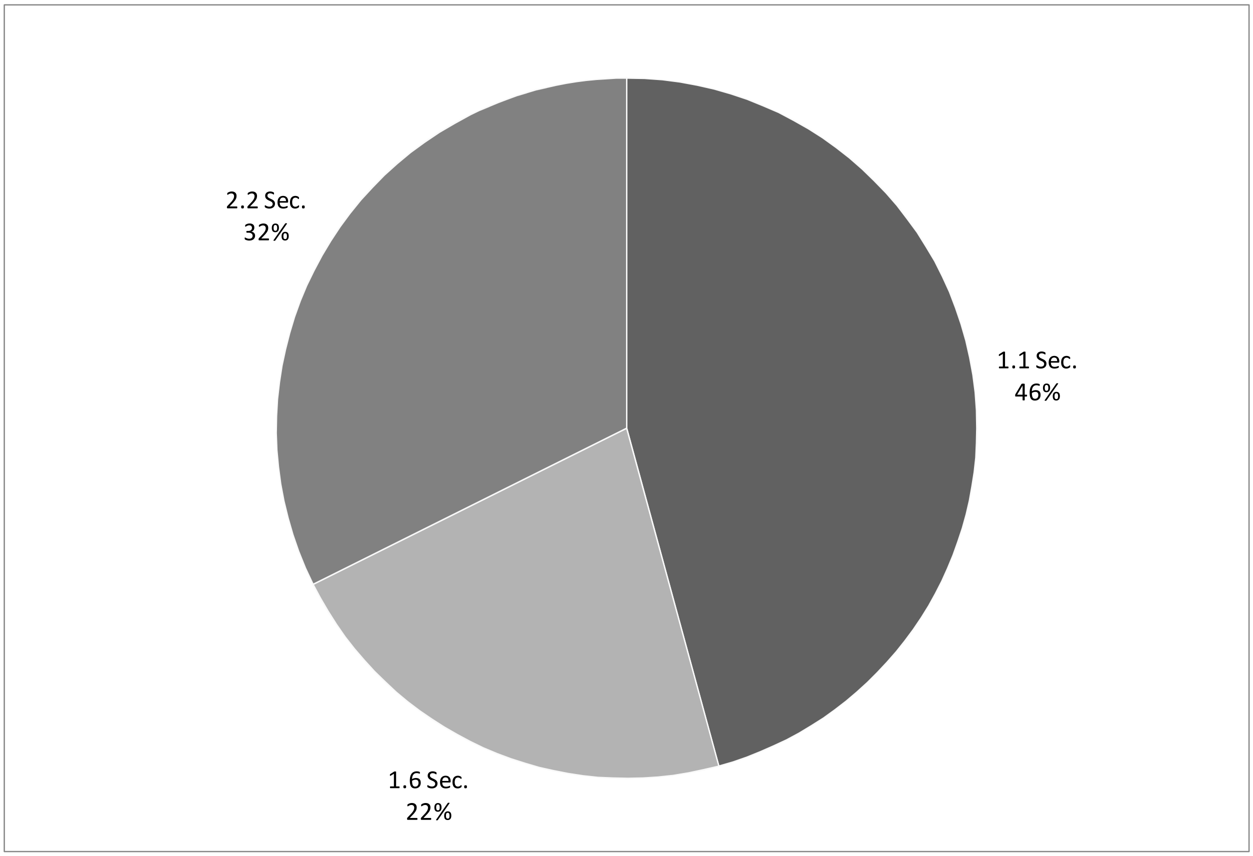

Figure 8.16: Distribution of time-gap settings with ACC system

Figure 8-16 displays the proportion of time each of the time gap settings was selected when the ACC was engaged. The gap that was most selected is the shortest gap available, which was selected nearly half of the time, while the second most selected gap was the longest one.

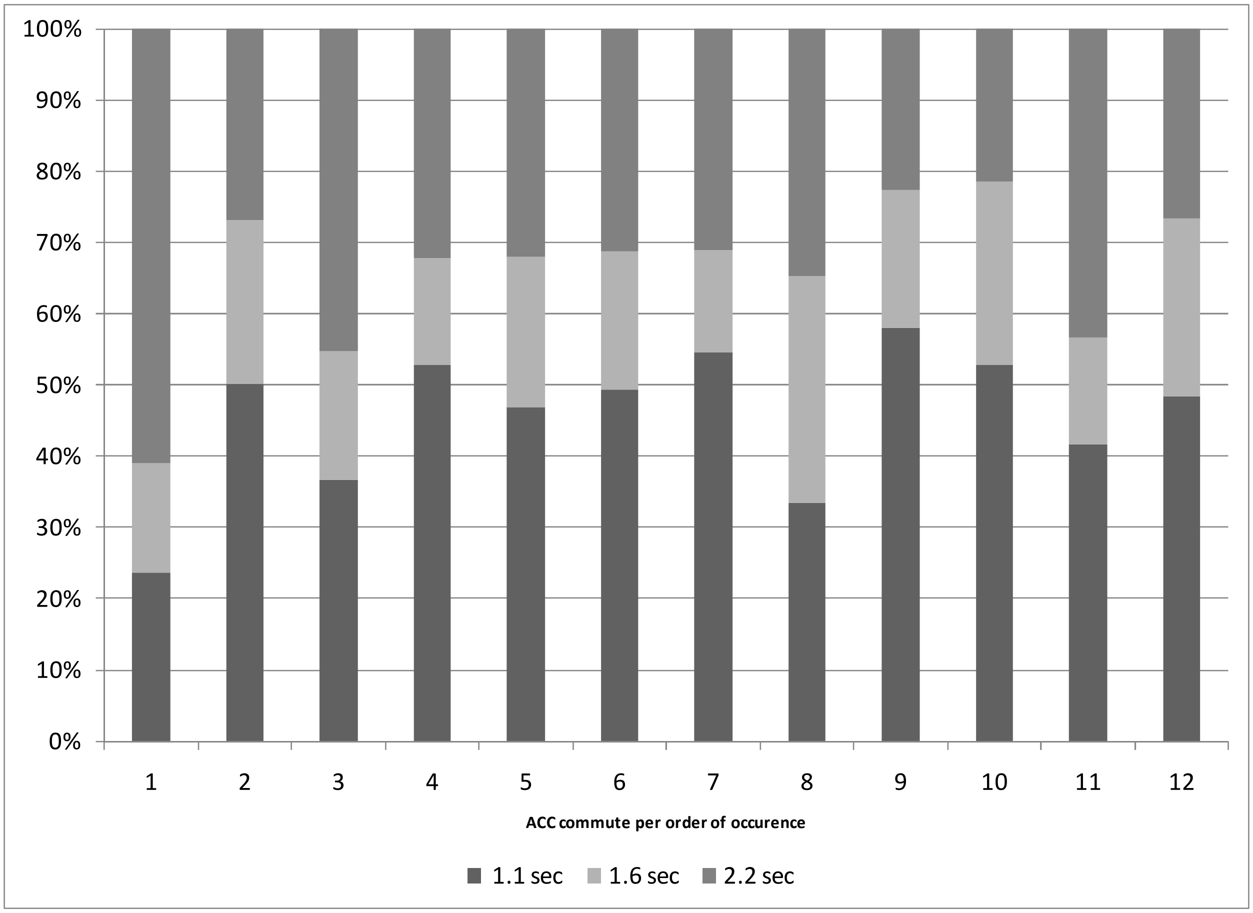

Figure 8.17: Proportion of time spent at each time-gap setting per ACC commute

Figure 8-17 displays the evolution in the proportion of time spent at each gap setting per ACC commute, from first trip to last, for all drivers. On the first day of use of the system, the longest gap is the most used, and becomes less used as the study progresses, with the exception of the 8th commute, where the medium gap use is more important than for any of the other commutes.

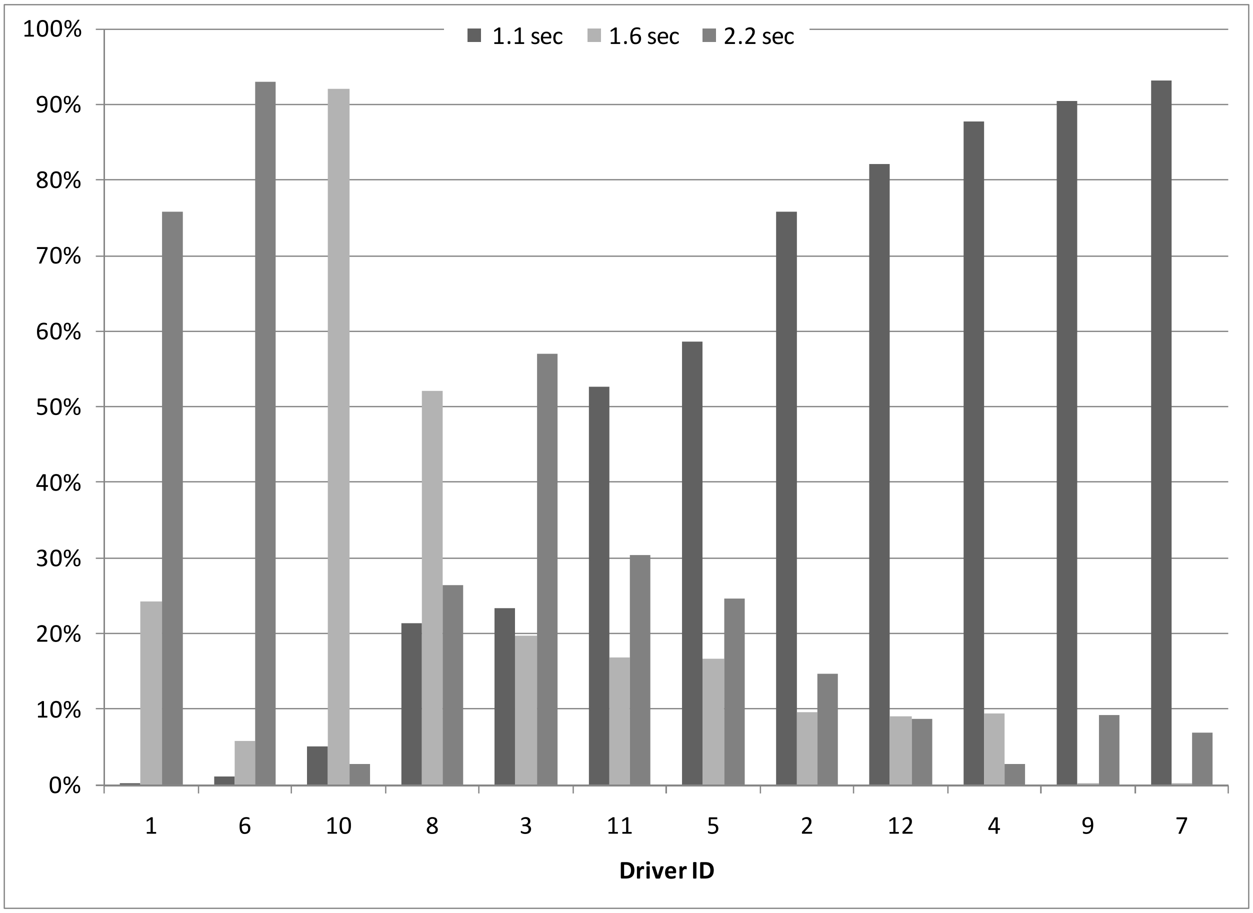

Figure 8.18: Distribution of ACC time-gap setting by driver

In Figure 8-18, we can see that the participant sample can be split in two based on the use of the shortest time gap, with drivers 1, 6, 10, 8 and 3 using another gap for a majority of the time, while the rest of the drivers used the smallest gap the majority of the time. It is noted that there is still a wide variation within these two groups, in the first one, in terms of the gap-setting the most used, as drivers 1, 6 and 8 used primarily the longest gap, and drivers 10 and 8 used the intermediate gap. In the second group, the use of the smallest gap varies from half of the time for driver 5 to almost all the time for driver 7.

8.3 Highway driving behavior with CACC

The description of highway driving with the CACC follows the same plan as the presentation of the ACC use given above.

<u>*8.3.1 Duration of CACC usage*</u>

The data have been sorted in 12 time based categories. The first two categories represent a half minute and the subsequent categories represent 1 minute increments.

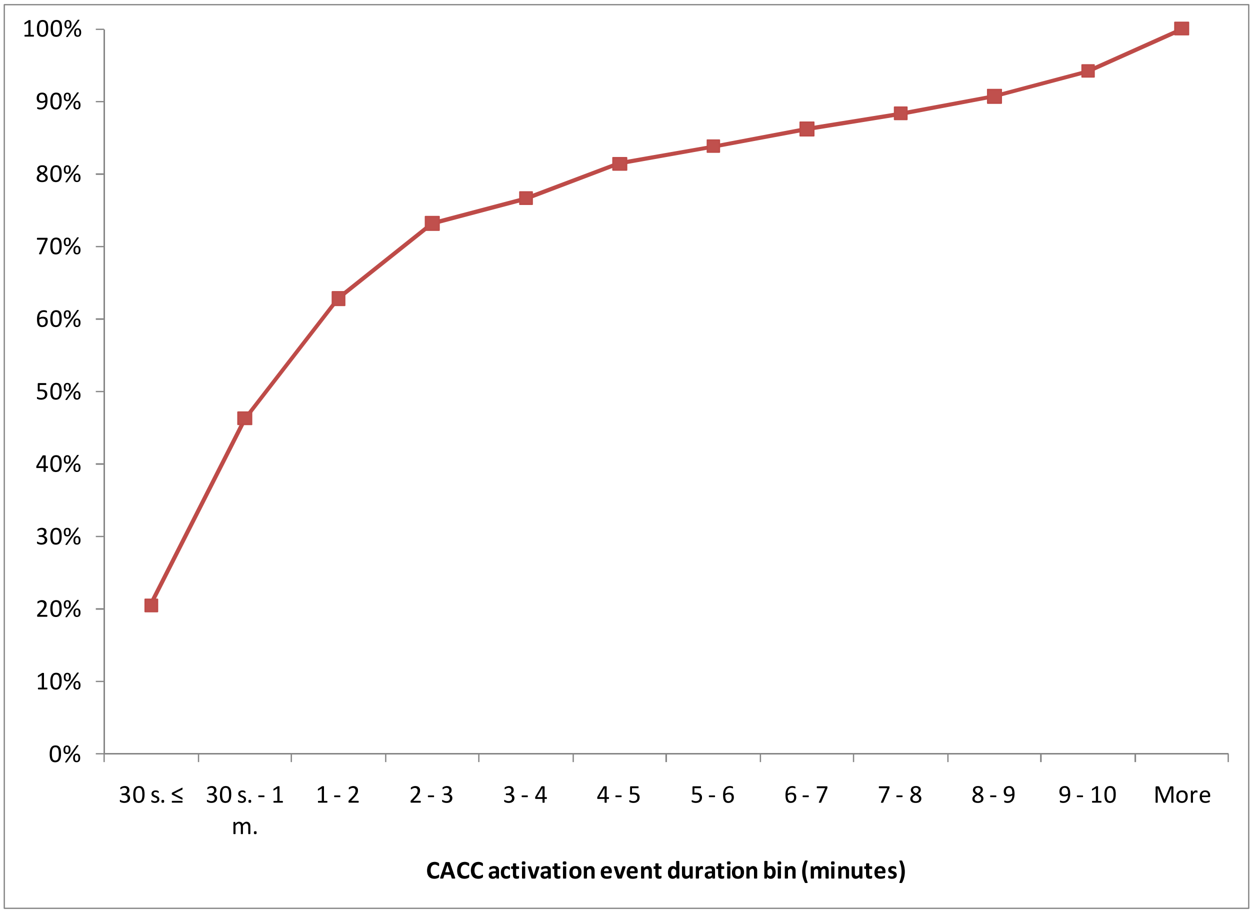

Figure 8.19: Distribution of CACC event duration

The cumulative distribution plotted in Figure 8-19 flattens near the 75th percentile, for events that lasted 2 to 3 minutes. The average activation duration is 2.95 min. (standard deviation of 3.7), with a minimum of 1 sec. and a maximum of 19.45 min.

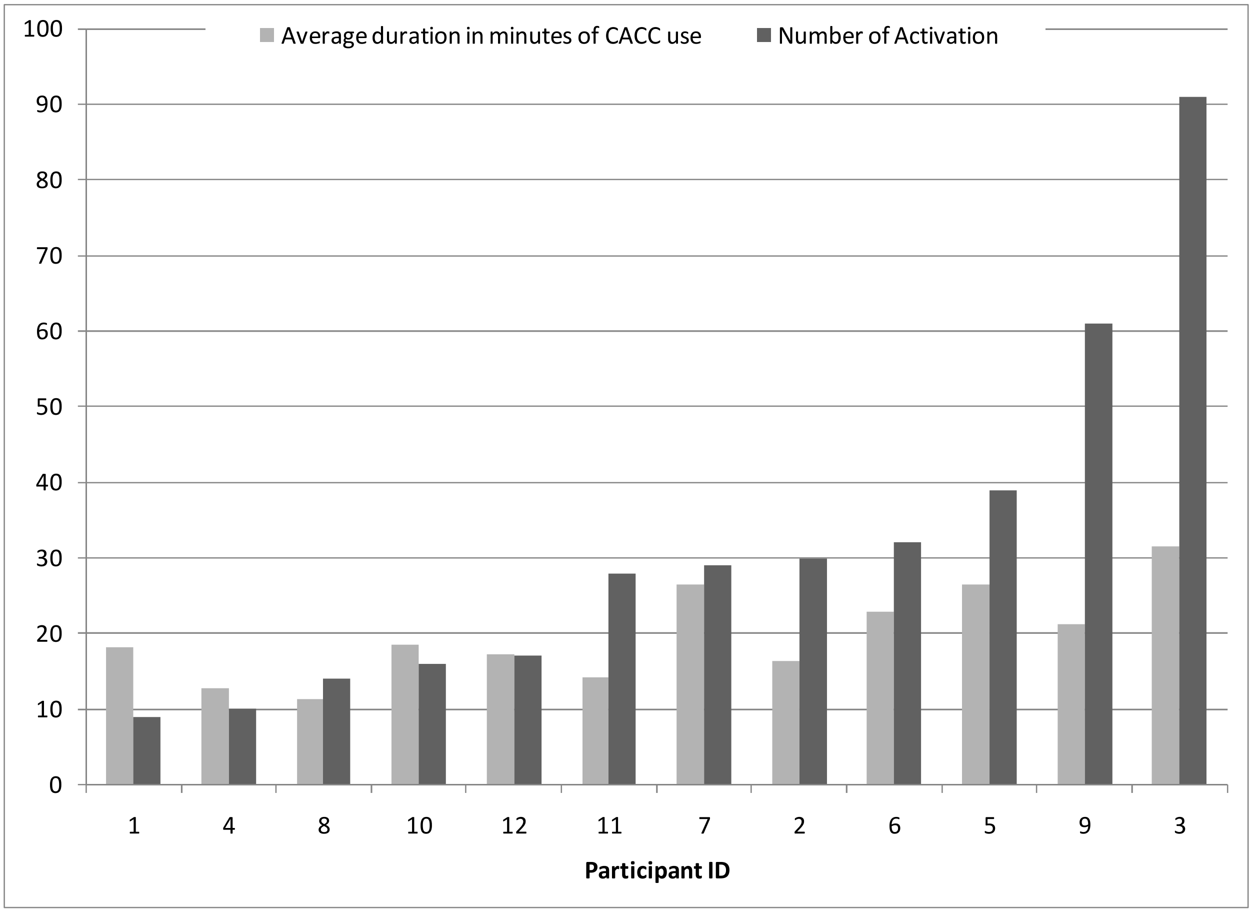

Figure 8.20: Average duration of CACC use and number of activation per participant

The data in Figure 8-20 have been ordered based on the number of activations. From this perspective, the first participant is the one with the lowest number of activations while driver 3 has the highest number of activations.

8.3.2 CACC activation and deactivation conditions

The parameters presented for the activation and deactivation of the system are the drivers' choices of gap settings and set speed. The speed control choices are presented first, followed by the choices of the time-gap settings.

8.3.2.1 CACC speed control choices

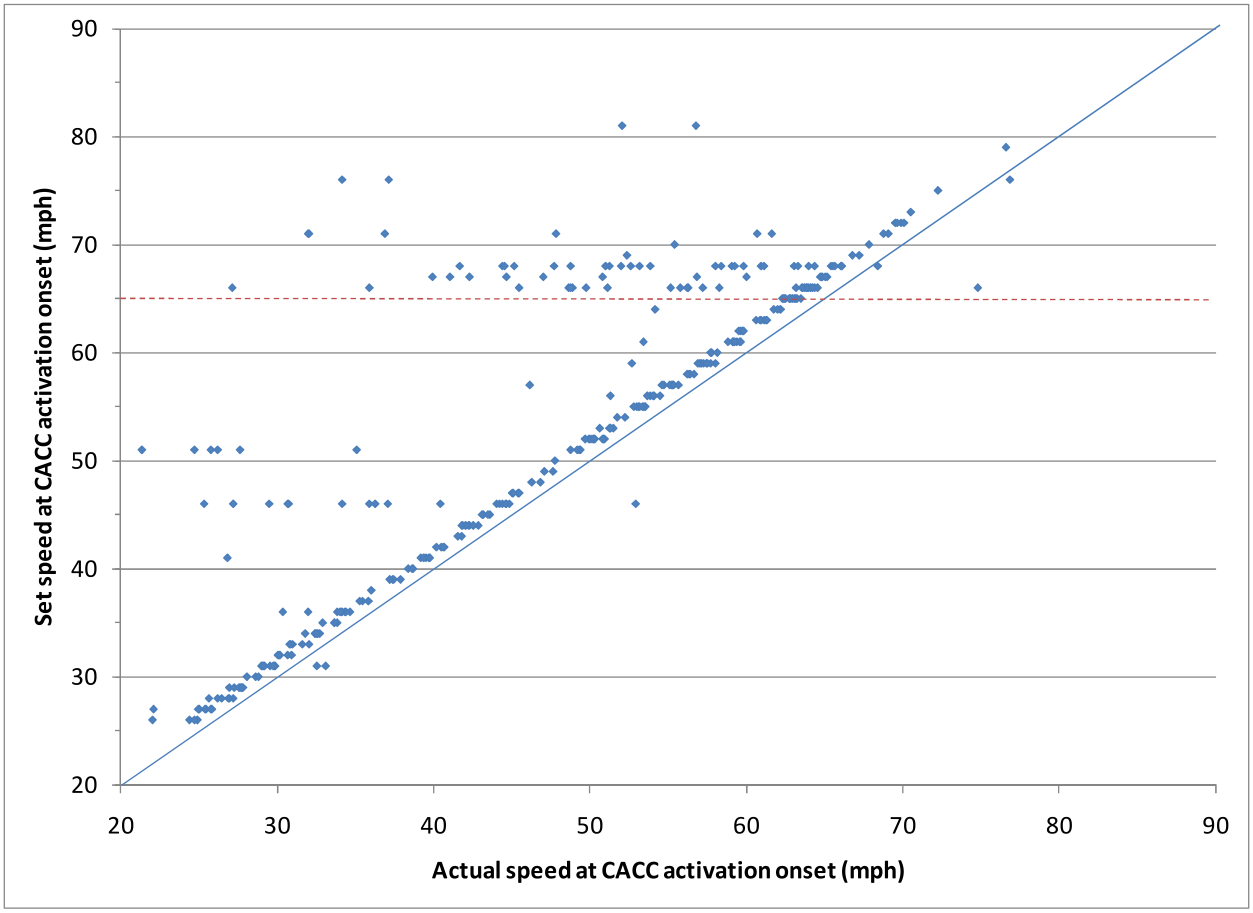

Figure 8.21: Actual speed at CACC system activation onset vs set speed

Figure 8-21 displays the actual speed of the CACC vehicle when the system was activated vs. the set speed. The same patterns can be identified as for the ACC system, i.e., that the majority of the speed setting are within 3 mph of the actual speed. This pattern is represented by the points following the solid line. This indicates that drivers used the set speed function most of the time. It also seems that there are two subgroups for the cases when the resume function was used. On the one hand, when the actual speed was lower than 40 mph, the resume function seems to have been used mainly for speed set at 50 mph, while when the actual speed was higher than 40 mph, the resume speed was above 65 mph. Further analysis will have to investigate the link between the first speed setting and the traffic density and how it evolved for the next activations, as a reason for these two tendencies could be due to low speed imposed by heavy traffic (cases under 40 mph) or sudden changes in the speed of traffic (cases above 40 mph).

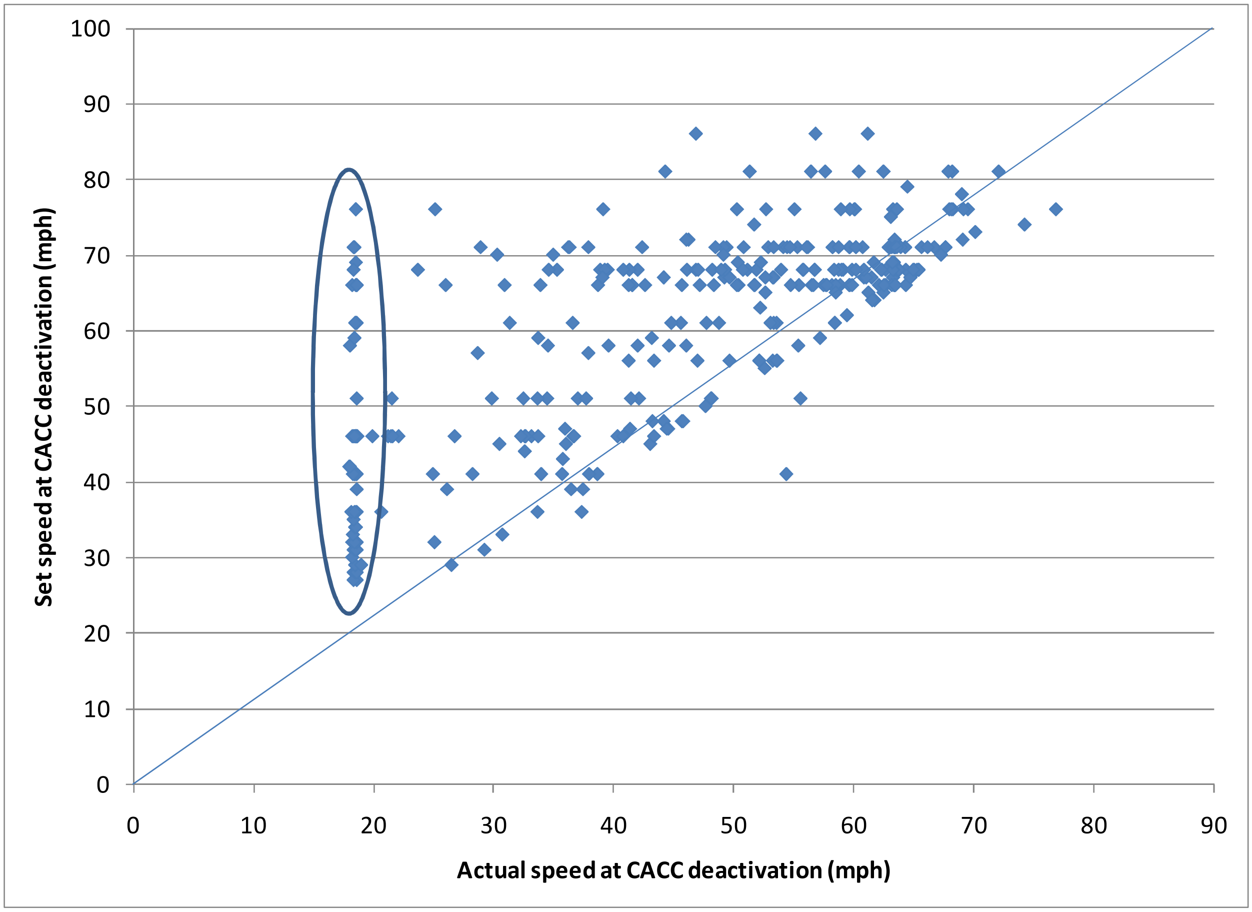

Figure 8.22: Actual speed at CACC system deactivation vs. set speed

In Figure 8-22, the plotting of the actual speed vs. the set speed when the system was deactivated offers a much more diffuse pattern than at activation time. The automatic shut-off of the system can be distinguished on the left side of the plot, at 20 mph of actual speed. Part of the data seems to follow the solid line, meaning that for these cases, the actual and set speed were identical, but for the most part, the set speed was higher than the actual speed when the system was deactivated. Future analyses will have to address the deactivations that occurred from non traffic related causes (e.g. leaving the highway) and those due to traffic, and assess the role of slower traffic on the decision to turn off the system.

8.3.2.2 CACC time gap setting choices

The time gap setting choices are described in terms of settings selected at the beginning and end of each activation, as well as the presence of a lead vehicle for these conditions and the size of the actual gap vs. the selected gap.

In order to describe the gap setting choices, the data have been sorted by activation order in the trip. Figure 8-23 illustrates the number of trips with each number of activations per trip.

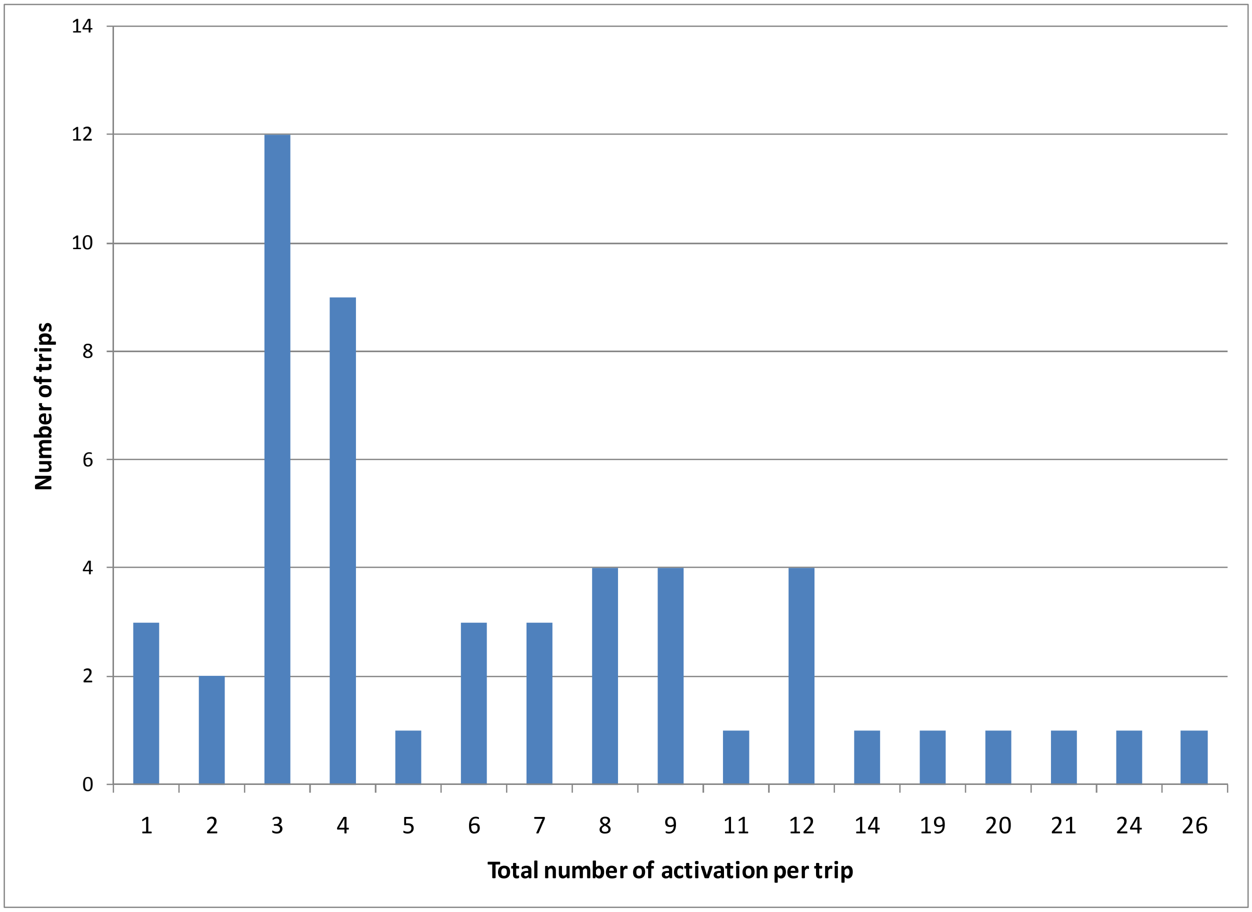

Figure 8.23: Number of trips by number of CACC activations per trip

Figure 8-23 shows that the maximum number of CACC activations within one trip was 26. The largest number of trips can be seen for three activations (12 trips), closely followed by four activations (9 trips). For simplicity of presentation, the results are shown for activations individually up to 10 and then the rest of the activations are collapsed into one category.

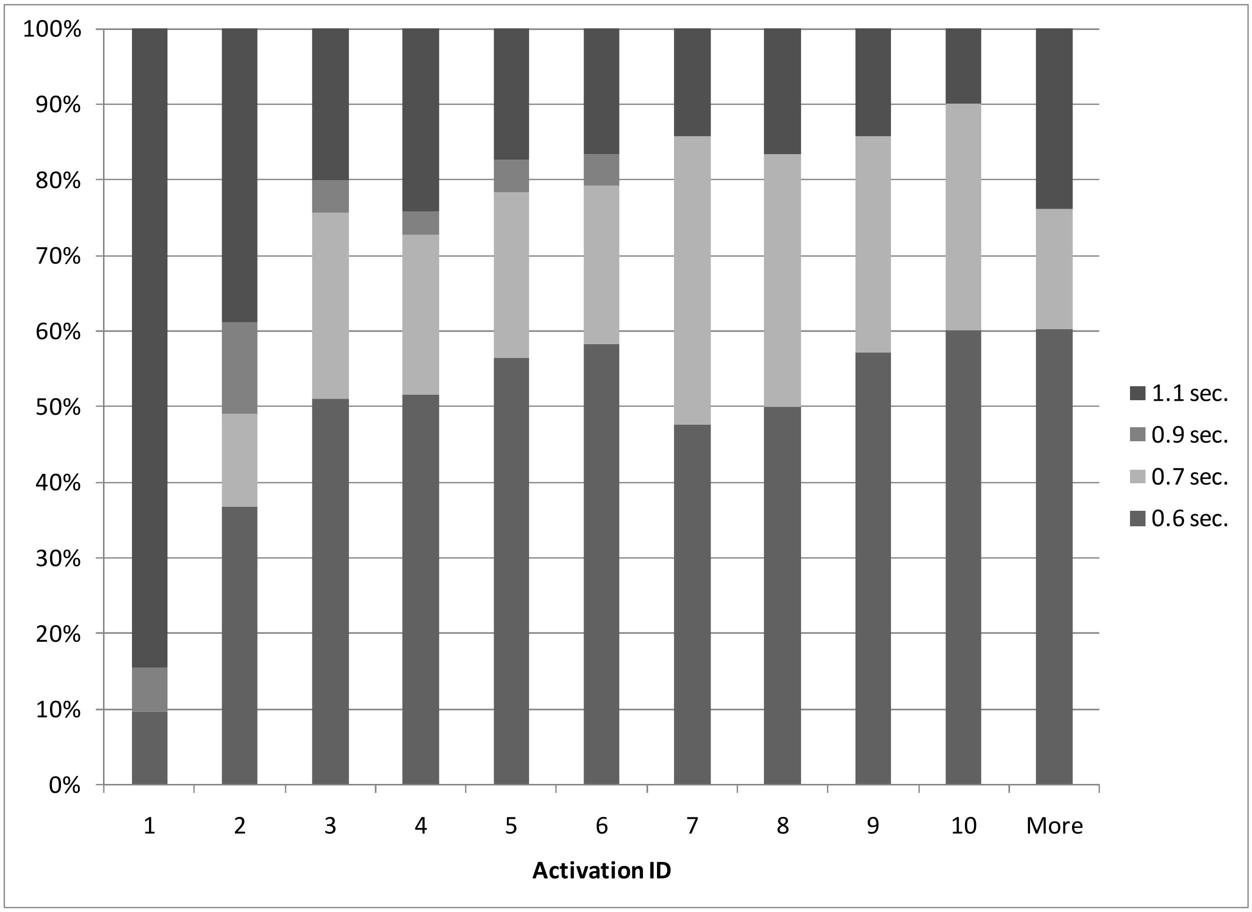

Figure 8.24: Distribution of time-gap settings at activation onset versus activation sequence within trip

Figure 8-24 illustrates that the gap setting for the first activation per trip is in the majority of cases at the longest setting. This is explained by the system's interface, which is at the longest setting by default when the system is activated. It is interesting to note that the proportion of use of the shortest gap increases from the second to the sixth activation, as does the use of the second shortest time gap, for activations 7 to 9. This change in the proportion of use of the second shortest gap could be due to the fact that only a few trips had up to 6 to 9 activations, and a driver using the second shortest gap could be over represented. This possibility will be investigated further in a later analysis.

Table 8.2: Categorization of actual gaps relative to gap settings – CACC system

CACC Gap setting	Classification based on range of actual gaps measured		
	Shorter gap range	Identical gap range	Longer gap range
0.6	0.2 to 0.4	0.41 to .8	>0.81
0.7	0.2 to 0.5	0.51 to 0.9	>0.91
0.9	0.2 to 0.7	0.71 to 1.1	>1.1
1.1	0.2 to 0.9	0.91 to 1.3	>1.3

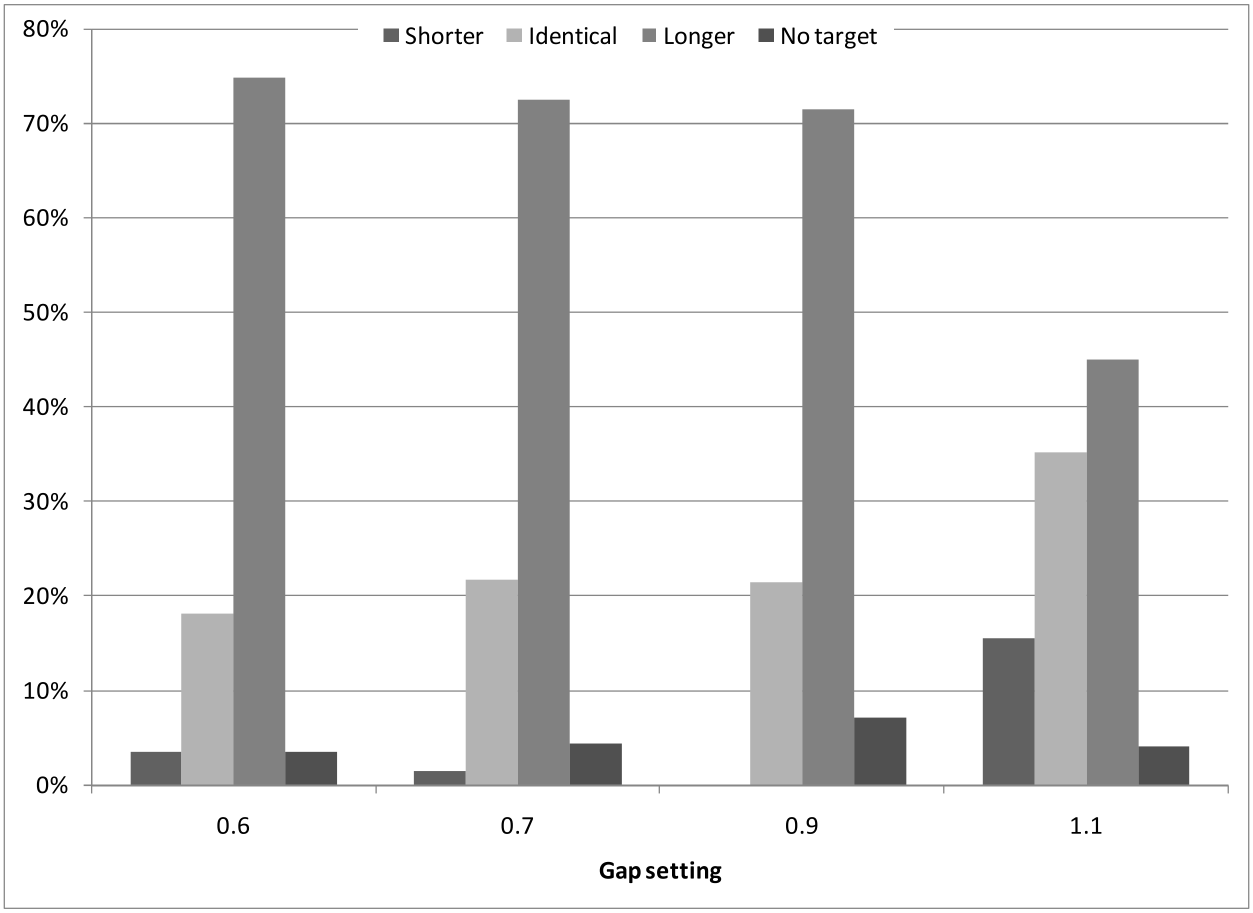

Figure 8.25: Distribution of actual gap size relative to gap setting at CACC activation

Figure 8-25 above displays the distribution of the size of the actual gap when the system was activated. For all settings, the system was activated when a target was in range in over 90% of the cases. For gap settings 0.6, 0.7 and 0.9 sec. the actual gap was longer than the gap regulated by the system in over 70% of the cases, while the gap was longer to identical for the 1.1 sec. setting. This means that when the drivers activated the system for the shortest settings, they let it close to the front vehicle to reach the desired gap.

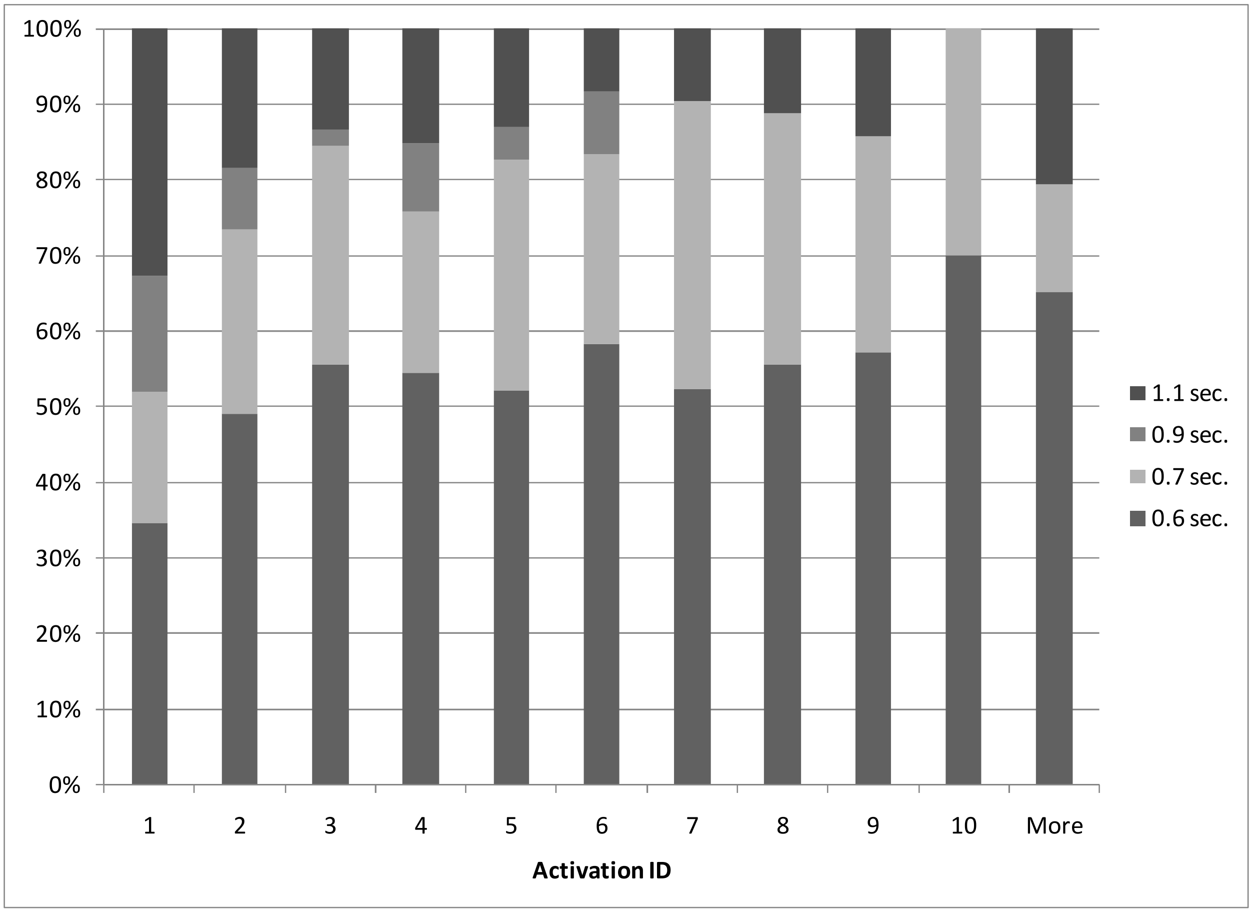

Figure 8.26: Distribution of time-gap settings at system's deactivation per activation occurrence

Figure 8-26 displays the proportion of gap settings at the end of each of the activations. The first point to highlight is the difference in the distribution of the longest gap relative to the start of the activation. In Figure 8-24, we saw that the 1.1 sec. time gap setting was selected for over 80% of the first activations, while it is the selected gap for only 30% of the first activations when the system is disabled. This indicates that for 50% of the first activations, the driver changed the gap within the first activation. The shift in proportion seems to be toward the two shortest gaps. A similar trend can be observed for the second activation.

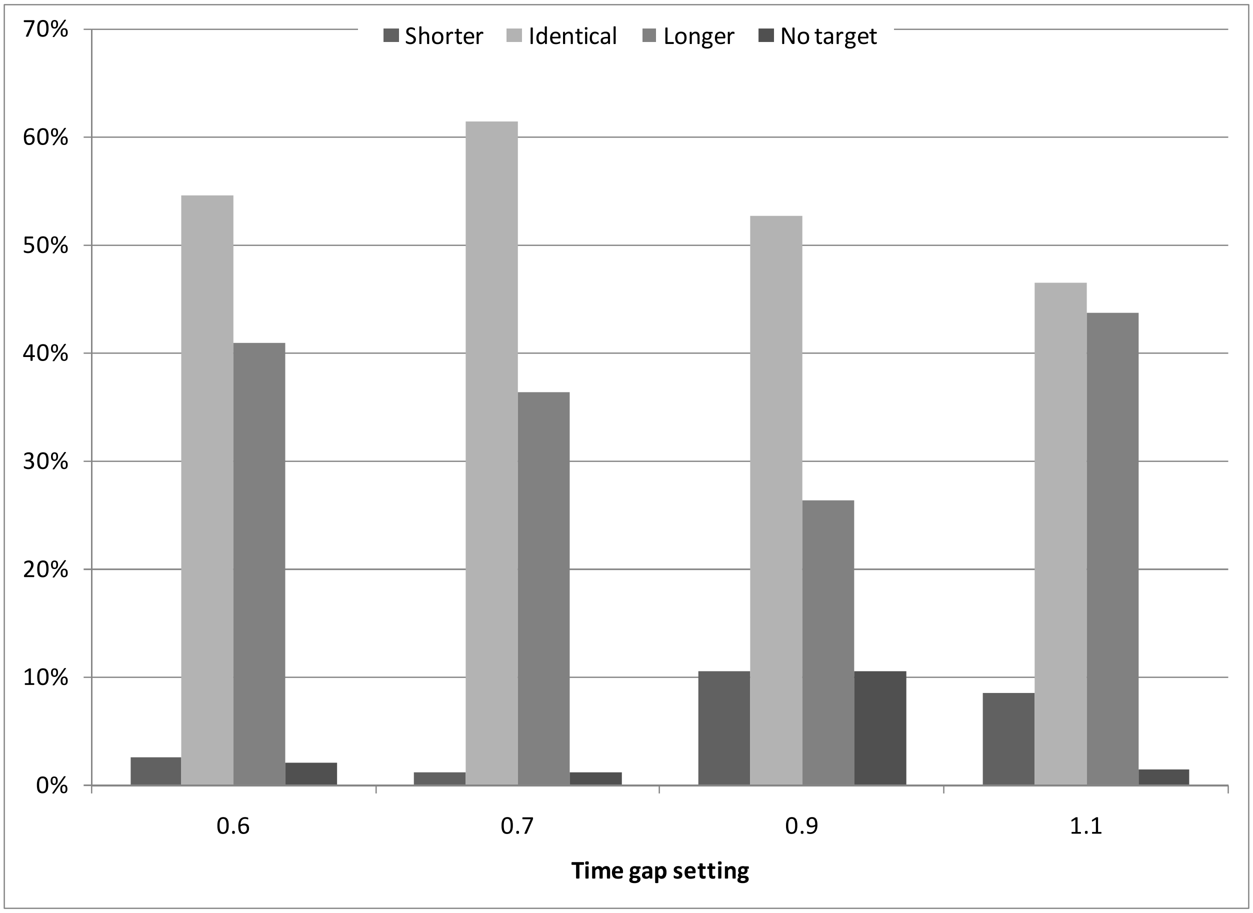

Figure 8.27: Distribution of gap size relative to gap setting at CACC deactivation

Figure 8-27 displays the size of the actual gap relative to the set gap when the system was deactivated. For all gap settings, a target was present when the system was deactivated for 90% of the cases. For the two shortest gap cases, a majority of the actual gaps were close enough to the set gap that they were categorized as identical, which means that when drivers deactivated the system it was probably actively regulating the gap. Further analysis will have to determine the proportion of interruptions due to the driver feeling that he/she needs to override the system vs. interruption due to other factors (e.g. leaving the highway). It is interesting to note that the actual gap is fairly evenly divided between identical and longer for the longest gap setting. This would indicate that the platoon between the two CACC vehicles was already breaking when the system was deactivated, which is all the more interesting as the longest gap seems to have been used primarily in the first activations within a trip.

8.3.3 Description of gap setting usage within CACC activations

Gap setting usage is presented in terms of distribution across all the drivers, based on the occurrence of the commute, and per driver.

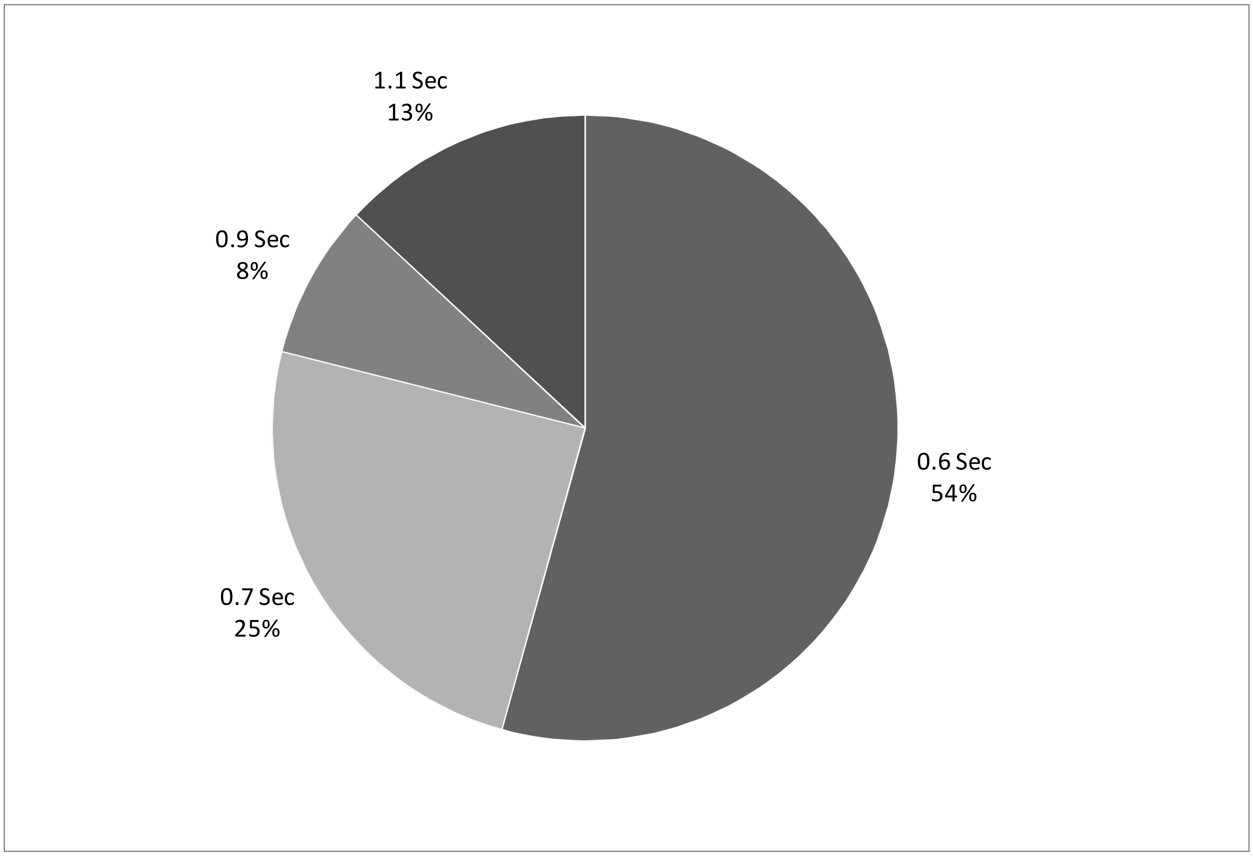

Figure 8.28: Distribution of CACC time-gap settings per drivers

Figure 8-28 above displays the proportion of time each of the gap settings were selected while the CACC system was engaged. The setting that was most often engaged was the shortest gap of 0.6 sec. followed by the 0.7 sec. The 0.9 sec. time gap seems to have been the least used, and was most likely a transition setting between the 1.1 sec. setting at the system's first activation and the desired shorter settings.

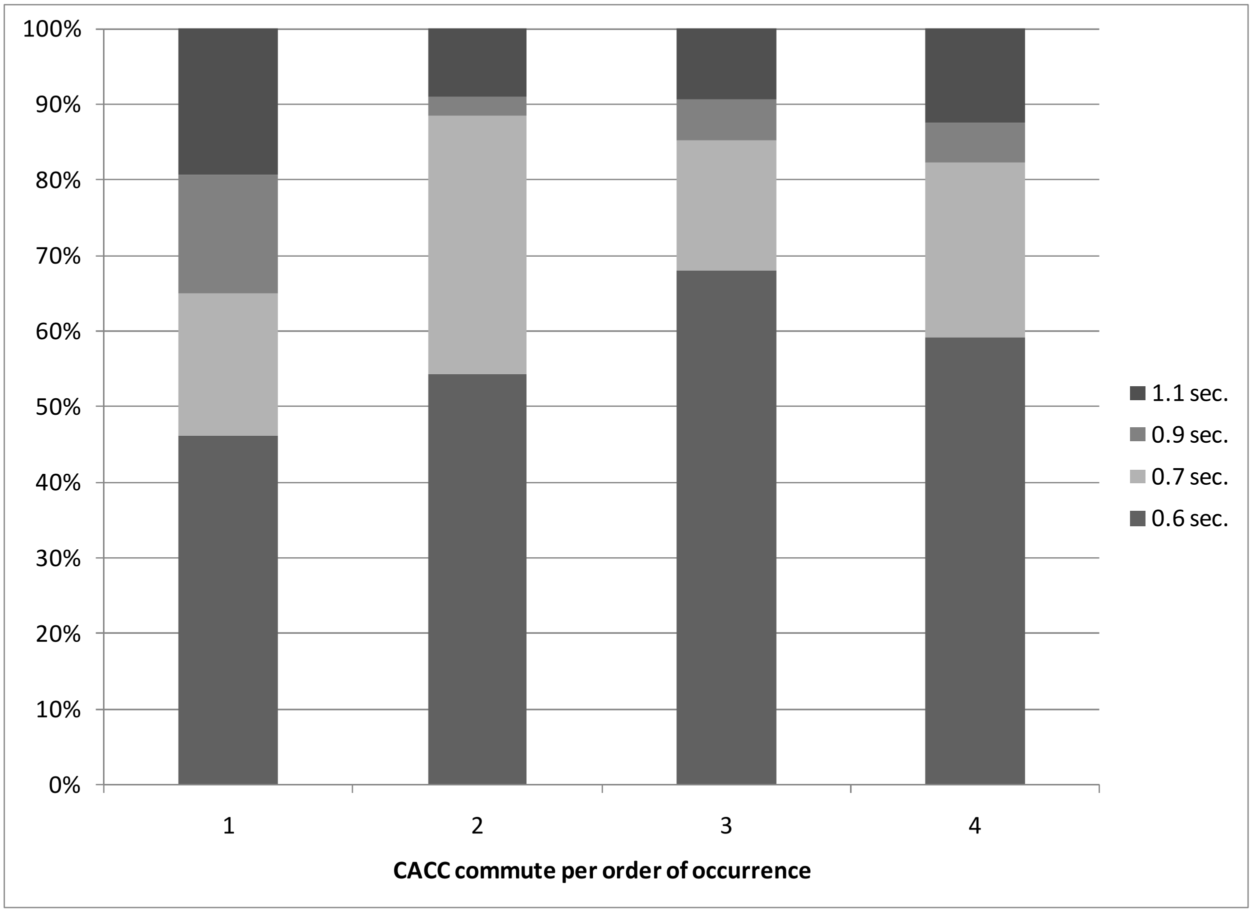

Figure 8.29: Proportion of time spent at each time-gap setting per CACC commute

Figure 8-29 displays how the proportion of time spent at each time setting changed based on the increasing exposure to the system. The usage of the shortest gap increased from the first to the third CACC commute, at the expense of the two longest gaps at first (commute 2) and then of all of the other gaps (commute 3). Its usage seems to decrease slightly on the last commute, due to an increase in the use of the 0.7 sec. gap.

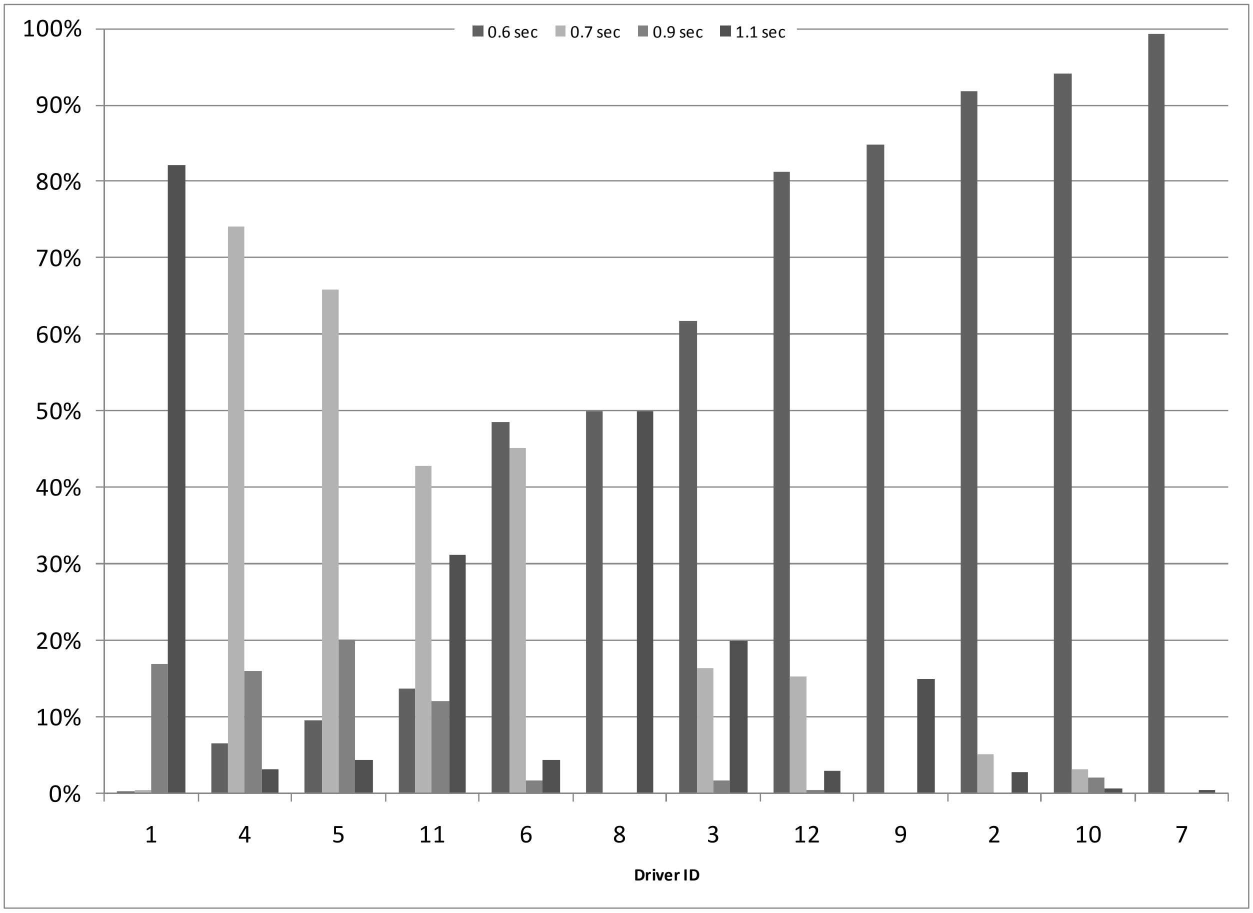

Figure 8.30: Distribution of time-gap settings by driver

The data in Figure 8-30 have been ordered based on the percentage of time spent at the 0.6 sec. time gap. Driver 8 represents the pivotal point between drivers using the system's shortest gap less and more than 50% of the time. Drivers 1 and 8 are marginal in the sense that they are the heaviest users of the longest gap setting, although driver 8 is interesting in that the only two gaps used by this participant were the longest and the shortest ones. Drivers 4, 5 and 11 preferred to use the second shortest gap of 0.7 sec, while driver 6 seemed to use the two shortest settings almost equally. Drivers 12, 9, 2, 10 and 7 used the shortest setting for more than 80% of the time they used the system.

8.4 Questionnaire Results – Subjective Impressions

The participants were given two questionnaires. The first was given to them after about eight days of driving the ACC vehicle. The second was given to them at the end of the test, after they had driven both the ACC and CACC vehicles. The questionnaire covered four basic topics:

1. Comfort and Convenience
2. Safety

3. Driving with the System
4. Road and Traffic Conditions

All of the first 12 participants filled out the ACC questionnaire, however, only ten of the participants filled up the CACC questionnaire. The questions were of three forms distributed among the topics presented above:

- Rating questions ranging from 1 to 7
- Ranking questions, where the participant expressed what system or driving mode was favored, usually from most preferred to least preferred
- Open ended questions, regarding the understanding of the system and eventual issues met when using the system.

The results that are presented differ for the rating and ranking questions. The mean and standard deviation are provided for the rating questions, while an index of preference was made for the ranking questions. The index was made by attributing a score based on the ranking, where the highest score indicates the highest preference. Responses from the open questions can be found in the appendix. The results of the questionnaire are presented below for each of the topics they covered.

8.4.1Comfort and Convenience

This topic was covered by 12 questions. The results are covered in Table 8-4, with the question that was asked, whether the answer was of the form of a rating or ranking. The responses are discussed below the table.

Table 0-3: Impressions about comfort and convenience.

Questions[3]	Answer	ACC (N=12)	CACC (N=10)
4 *(2)*. Overall, how comfortable did you feel driving the car using the C/ACC system?	Rating	1 to 7 (most comfortable)	
	Mean	5.83 (.83)	6.1 (.56)
8 *(6)*. How easy was it to drive using the C/ACC system?	Rating	1 to 7 (most difficult)	
	Mean	2 (1.47)	1.7 (.94)
12 *(11)*. What was your level of comfort for each of these gaps with the ACC?	Rating	1 to 7 (most comfortable)	
Long gap	Mean	5.5 (1.56)	5.4 (1.8)
Medium gap		5.75 (1.54)	5.4 (1.5)
Short gap		4.92 (2.02)	5.3 (1.56)
Shortest gap		-	5 (2.3)

[3] Most of the questions were identical for both system and are merged for simpler presentation. The first question number refers to the ACC questionnaire, the second question number refers to the CACC questionnaire. For questions pertaining to the ACC and CACC system, the system's name takes the form of C/ACC.

16 *(14)*. How long did it take you to be comfortable using the C/ACC system?		1.25 days (.45)	0.75 days (.40)
18 *(16)*. How comfortable were you driving the C/ACC system in comparison to the manual driving?	Rating	1 to 7 (more comfortable)	
	Mean	4.42 (1.61)	4.9 (1.5)
26 *(24)*. How likely is it that you would have become more comfortable using the C/ACC system given more time?	Rating	1 to 7 (very likely)	
	Mean	5.08 (2.57)	5.7 (1.94)
30 *(29)*. Compare these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for comfort	Rank	Preference index Highest score = most comfortable	
	MD	28	26
	CC	15	13
	ACC	29	29
	CACC	-	32
33 *(25)*. Compare these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for convenience	Rank	Preference index Highest score = most convenient	
	MD	18	20
	CC	17	13
	ACC	31	26
	CACC	-	31
36 (35). Compare these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for driving enjoyment	Rank	Preference index Highest score = most enjoyable	
	MD	20	21
	CC	16	12
	ACC	29	27
	CACC	-	30
44 *(46)*. Rank, in order of preference, the following modes of operation (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*) for personal use.	Rank	Preference index Highest score = most desirable	
	MD	21	25
	CC	16	13
	ACC	29	29
	CACC	-	33

Participants felt relatively comfortable driving with the ACC and overall rated their level of comfort with the CACC even higher, which can be interpreted either as a higher level of comfort with the CACC or the result of a longer exposure to the technology, as pointed out by the responses to question 26/24 indicating for both systems that drivers still expected to become more comfortable with the system if given more time with it. A similar case can be made about the ease expressed by the drivers for driving with either system, and where the CACC received a slightly better rating than the ACC. The time needed for learning to use the system was considerably shorter for the CACC, since the drivers were already familiar with the ACC.

In terms of comfort with each of the gap settings, the medium gap with the ACC received the highest rating in terms of comfort, although the difference with the other gaps is relatively negligible. The responses to the CACC questionnaire do not permit to identify one of the gaps as either most or least comfortable overall.

When drivers ranked the operation modes, it is clear that the conventional cruise control system was the least liked of all options and this across all of the questions. The responses to the ACC questionnaire indicate that the system is deemed equally comfortable to manual driving and received higher scores than manual driving in terms of convenience, driving enjoyment and personal use. The responses to the CACC questionnaire indicate a similar trend, with the CACC and ACC receiving higher scores than manual driving, and the CACC system receiving slightly higher scores than the ACC.

In the ACC questionnaire, in response to question 40: Would you rather have: An ACC, a CC or no system, all but one participants chose the ACC, while participant 12 prefers to have no system.

In the CACC questionnaire, to the question: Between the ACC and CACC system, did you prefer one of the systems? All participants replied yes, with 2 participants (1 and 5) preferring the ACC and the other 8 preferring the CACC. To question 40: Which would you rather have? Participants 8 and 12 answered no system, 1 and 5 the ACC, while the 6 other participants chose the CACC.

8.4.2 Safety

This topic was covered by ten questions. The results are summarized in Table 8-5 and the responses are discussed after the table.

Table 0-4: Impressions about safety.

Questions	Answer	ACC	CACC
5 *(3)*. Do you think C/ACC is going to increase driving safety?	Rating	1 to 7 (Strongly agree)	
	Mean	5 (1.47)	4.9 (.99)
9 *(7)*. Compare safety under these operation modes (manual driving, Cruise Control, Adaptive Cruise Control, *Cooperative Adaptive Cruise Control*)	Rank	Preference index Highest score = most safe	
	MD	34	28
	CC	11	10
	ACC	26	26
	CACC	-	26
13 *(9)*. Under which mode of operation did you feel you reached your destination most safely?	Rank	Preference index Highest score = most safely	
	MD	30	26
	CC	12	10
	ACC	24	27
	CACC	-	27
17 *(15)*. When driving the C/ACC system, compared to manual driving, were you more or less aware of the actions of vehicles around you than you normally are?	Rating	1 to 7 (More aware)	
	Mean	4.42 (1.08)	4.6 (1.26)
19 *(21)*. How frequently did you get into situations when you relied too heavily on the C/ACC to handle situations that it could not handle?	Rating	1 to 7 (Never)	
	Mean	5.58 (1.08)	5.6 (1.3)
25 *(23)*. How much effort did it take to maintain a safe following distance when using each of the following modes of operation?	Rating	1 to 7 (Very easy)	
Manual driving	Mean	5.58 (1.16)	4.3 (1.41)
Cruise Control		3 (1.12)	3.2 (1.47)
ACC		6.5 (.52)	5.5 (1.26)
CACC		-	5.8 (1.29)
28 *(28)*. How often, if ever, did you experience “unsafe” following distances when using the **C**/ACC system?	Rating	1 to 7 (Never)	
	Mean	4.58 (1.44)	4.8 (1.87)
29 *(40)*. Driving the C/ACC system, compared to manual driving, did you find yourself more or less responsive to actions of vehicles around you?	Rating	1 to 7 (more responsive)	
	Mean	4.18 (1.16)	4.7 (.82)
34 *(NA)*. While using the ACC system, how often, if ever, did the system fail to detect a vehicle that you were approaching or following?	Rating	1 to 7 (Never)	
	Mean	5.75 (1.21)	NA
37 *(36)*. How safe did you feel using the C/ACC system?	Rating	1 to 7 (very safe)	
	Mean	6.08 (.99)	5.6 (1.17)

The participants thought that there is potential for these systems to increase safety. The responses to the ACC questionnaire indicate that drivers found it easiest to maintain a safe following distance with the ACC, but they still rated manual driving as the operation mode allowing them to reach their destination the most safely. Greater exposure to the system might also explain the difference in rating for the ACC, which receives a similar rating as the CACC and manual driving after the CACC test for this same question. However, the rating for the ease with which to maintain a safe gap seems to have been affected by the CACC test for the manual and ACC mode of operation, as these two modes receive lower ratings for the ease to maintain a safe gap on the CACC questionnaire. Even though the ACC and CACC are seen as the mode with which it is easiest to maintain a safe gap, the responses do not seem as overwhelming as they were for the ACC only.

The participants did not feel that either system affected their awareness or responsiveness to other vehicles, or that they were relying too heavily on the system. The responses also indicate that the participants did not feel that they experienced a lot of unsafe following distances with either system.

8.4.3 Driving with the system

This topic was covered by ten questions. The results are covered in Table 8-6 and the responses are discussed after the table.

Table 0-5: Impressions about driving style.

Questions	Answer	ACC	CACC
7 *(5)*. In general, under which mode of operation (Manual, Conventional Cruise, C/ACC) did you feel like you reached your destination fastest?	Ranking	Preference index Highest score = fastest	
	MD	29	24
	CC	13	11
	ACC	18	22
	CACC	-	23
10 *(43)*. Do you feel the following adjustment function is useful?	Rating	1 to 7 (Strongly agree)	
	Mean	5.25 (2.22)	6.7 (.67)
15 *(13)*. Which mode of operation (Manual, Conventional Cruise, C/ACC) required you to apply the brakes most often?	Ranking	Preference index Highest score = least often	
	MD	20	18
	CC	21	19
	ACC	19	26
	CACC	-	36
23 *(NA)*. What did you think of the acceleration provided by the ACC system when pulling into an empty adjacent lane to pass other vehicles?	Rating	1 to 7 (too fast)	NA
	Mean	3.75 (.96)	
24 *(22)*. What did you think of the deceleration rate provided by the C/ACC system when following a vehicle?	Rating	1 to 7 (too hard)	
	Mean	3.92 (1.16)	4.2 (1.47)

32 *(32)*. Did you feel more comfortable performing additional tasks, (e.g., adjusting the climate control or the radio) while using the C/ACC system as compared to driving under manual control?	Rating	1 to 7 (strongly agree)	
	Mean	5.08 (1.38)	-
35 *(33)*. As you got used to the C/ACC system, how would you rate the change of your level of confidence in the system?	Rating	1 to 7 (Less confident)	
	Mean	2.17 (.83)	2.4 (.96)
39 *(38)*. When using the C/ACC system, did you ever feel that you didn't understand what the system was doing, what was taking place, or how the C/ACC system might behave?	Rating	1 to 7 (very infrequently)	
	Mean	5.33 (1.87)	5 (1.82)
41 *(42)*. In general, under which mode of operation did you feel like you reached your destination with the least stress related to driving?	Ranking	Preference index Highest score = least stress	
	MD	19	17
	CC	16	15
	ACC	31	32
	CACC	-	36
42 *(8)*. While driving with the C/ACC, how confident did you feel about the system?	Rating	1 to 7 (Not confident)	
	Mean	2.08 (1.44)	2.2 (1)
45 *(47)*. When you were driving with the C/ACC, were you driving slower or faster than you normally drive?	Rating	1 to 7 (faster)	
Heavy traffic		3.17 (1.11)	3.5 (1.35)
Medium traffic		3.5 (1.087)	4.2 (.9)
Light traffic		3.33 (1.07)	4.1 (.99)

When ranking the mode of operation for reaching their destination the fastest, manual driving received the highest score under the ACC questionnaire, while the ACC and CACC system scored similarly to manual driving under the CACC questionnaire. However, the participants rated that they were going rather slower with either system vs. manual driving for any traffic density, though the difference in speed seems to become more neutral for the light traffic condition for the CACC.

Drivers expressed a high confidence in both systems and felt that their level of confidence increased as they became more familiar with the systems. They also rated the systems as the least stressful mode of operations, requiring the least amount of braking under the CACC questionnaire. The ranking of systems based on the amount of braking for the ACC questionnaire showed no preference for any mode. This seems to indicate that the drivers were most likely still becoming familiar with the ACC system when filling out the first questionnaire, and that as their level of comfort increased; they used the brake less often.

8.4.4 Road and traffic conditions

This topic was covered by four questions. The results are covered in Table 8-7 and the responses are discussed after the table.

Table 0-6: Impressions about the impact of road and traffic conditions on ACC and CACC use

Questions	Answer	ACC	CACC
6 *(4)*. When using the C/ACC system in each of the following traffic conditions, did you follow other vehicles closer or further than you normally do?	Rating	1 to 7 (Further)	
Heavy traffic	Mean	5 (1.3)	4.1 (1.2)
Moderate traffic		4.58 (1.3)	3.4 (1.35)
Light traffic		4.33 (1.15)	2.8 (1.13)
14 *(12)*. How comfortable were you using the C/ACC system when driving in the following traffic environments?	Rating	1 to 7 (Very comfortable)	
Heavy traffic		4.17 (1.9)	4.5 (2)
Moderate traffic		5.75 (1.2)	5.7 (1.16)
Light traffic		6.5 (1.4)	5.8 (1.62)
20 *(17)*. When you were driving with the C/ACC, was your speed generally slower or faster than the speeds of neighboring vehicles?	Rating	1 to 7 (Faster)	
Heavy traffic	Mean	3.42 (.8)	3.9 (.99)
Medium traffic		3.83 (.9)	4.3 (.67)
Light traffic		4.33 (1.15)	4.2 (1.31)
27 *(27)*. How comfortable were you using the C/ACC system on hilly roads?	Rating	1 to 7 (Very comfortable)	
		6 (1.32)	5.43 (1.27)

Traffic density impacted the perception of both systems relative to manual driving. With the ACC, drivers rated that they were following vehicles further away under heavy traffic but similarly to manual driving when traffic was moderate or light. The ratings for the CACC show that drivers felt that they followed at about the same range with the system as they would under manual control for heavy traffic, but followed closer when using the system with moderate or light traffic.

Traffic density also affected how comfortable the participants were using the system. They rated that they were less comfortable with the system under heavy traffic and rather comfortable when using either system when the traffic was light, more so for the ACC. The density slightly affected the perception of the participants' speed vs. the surrounding vehicles. Drivers felt that they were going slightly slower under heavy traffic and at about the same speed as traffic under moderate and light traffic conditions.

8.5 Summary of driver usage of ACC and CACC

The experimental plan included testing of the ACC as a transition phase for the participants to get familiar with a technology new to them, since the level of public awareness and market penetration of ACC systems remains very low. From this perspective, we cannot compare the ACC and CACC in terms of what system was preferred, but rather understand the results from the angle that the familiarity and comfort gained with the ACC allowed for testing of a prototype CACC with shorter gaps than can be provided with systems currently on the market.

The ACC was well received by the majority of the participants, as can be seen with the questionnaire results, where 11 out of 12 participants would rather have an ACC than no system. Participants expressed high levels of comfort and confidence in the system, and reported few if any worrisome situations. Similarly, the CACC was well received by the participants, as 8 out of the 10 participants who filled out the questionnaire would rather have a CACC than no system.

The data collected during highway driving with the systems show that the shortest settings were the most used settings for both systems, although there is a fair variability among the participants. For the CACC, approximately half of the sample drove mostly with the shortest time gap setting of 0.6 sec. for most of the CACC testing when the system was engaged. For the other half, the 0.7 sec setting was preferred, with the exception of one participant who preferred the longest setting. These preliminary results indicate that drivers would most likely use a CACC system at gap settings as short as 0.7 to 0.6 sec.in urban commuter trip driving.

Appendix: Answers to open questions from ACC and CACC questionnaires

Adaptive Cruise Control Survey

D01-Question 3 ACC is regular cruise control plus the ability to maintain a preset (but variable) following distance. The maximum speed is set via the cruise control, but ACC will automatically accelerate and brake the vehicle in order to maintain the following distance the driver sets.
D01-11 I didn't like the way it would handle in heavier traffic when other cars would merge in front of me into the open gap—it would brake suddenly because it wouldn't slow down until the other car was almost completely done merging. This was also similar to the way it behaved when driving in the far right lane and other cars were entering the highway from the on-ramp.
D01-21 I was pleasantly surprised at the way it handled when other vehicles would merge after passing (accelerating as they merged in front of you). I expected more braking because of the small distance available but it performed the way I would have driven.
D01-31 Add sensors to the side to detect when another vehicle is in the process of merging in front of your vehicle. This would avoid the only unsafe situation I encountered.
D01-38 N/A I thought the system was fairly well designed regarding the user interface.
D01-43 n/a

D02-3: blank
D02-11 With short gap set, abrupt changes in traffic speed were not seen quickly enough. For example, traffic slowing abruptly from 65 to near stopped, the distance where the car would slow was far too short for comfort.
D02-21 NO
D02-31 Instead of distance only, it would be interesting to have an ACC based on (or including) speed of the vehicle in front. A minimum gap threshold could be set, but add a model for a gap closing rate as well to avoid rapid discontinuities in forward vehicle speed.
D02-38 I thought the longest gap was too long and didn't like having to reset it each time engaged to shorter gap. Speed increase is a bit hair trigger, if not paying attention goes quickly to 90 mph.
D02-43 NO
Further comment: I felt more comfortable with lane changes, especially in traffic, because I could take my eyes off the forward vehicle and look at my blind-spot and know that my car would give me some indication that the car in front was slowing (i.e., braking).

D03-3 Adaptive Cruise Control is a safety feature that allows setting both the speed and the following distance relative to the car in front. The speed adjusts automatically (not

above the set limit) to maintain the following distance. There is a drawback: ACC doesn't work in stop and go traffic.
D03-11 Yes, sometimes cars change lanes and suddenly get in front. Although they were not quite cutting in front (still some distance between the car I drove and the car changing lanes) when the car I was driving was on ACC speeding up to the set speed, many times I felt it might not stop in time to avoid bumping into the car that just changed lanes.
D03-21 Not really.
D03-31 Make ACC accessible at stop and go traffic too. I think it will increase safety by avoiding constantly maintaining the distance from the car in front it can avoid fender-benders.
D03-38 Climate control is difficult to set for higher temperatures. It distracts from driving while trying to figure out how to adjust the climate.
D03-43 NO

D04-3 Adaptive cruise control is like cruise control, where you can set your car's speed, but then the car adapts to a set distance, too, gauging by lasers in front how far the car ahead is!
D04-11 i) in very heavy traffic (0-25 mph), ii) exiting the highway, iii) at toll bridges and approaching.
D04-21 Just with how responsive/reactive it is—I was surprised at how quickly it responds to other cars sudden movements (e.g., lane changes) and that you can "feel" the car reacting.
D04-31 Not sure, maybe an added gauge (digital) telling me what my actual speed is (vs. set speed)
D04-38 Not sure yet—system still too new for me to determine what I am not using, or taking for granted!
D04-43 NO

D05-3 A system that automatically slows or speeds up per setting by driver. Instead of the regular cruise control system, this system allows you to set the spacing between your vehicle and the vehicle in front of you. Based on that distance, your vehicle will ensure that it maintains that distance.
D05-11 The distance setting for closest to vehicle in front was not as comfortable. I do not trust the distance setting and found that it was not as consistent as the other two distance settings.
D05-21 Only when using the close distance setting. Seemed to brake closer than I would when driving manually.
D05-31 Can not think of anything to add. The system seems to work great!!
D05-38 Modify the closest setting. Distance for slowing or stopping seems to be too close. I was not comfortable with the system at the distance setting.
D05-43 NO

D06-3 Radar determines the distance between you and the car ahead and adjusts your speed accordingly.
D06-11 When traffic came to a sudden stop and brake high speed. The car would

not brake as quickly as I would like.
D06-21 no answer.
D06-31 no answer
D06-43 no answer

D07-3 Its cruise control that adjust the speed of the car based on the distance of the car in front of you. If you set the speed at 80 and no car is in front of you then the car will maintain a speed of 80 but when an object (car) comes in front of the car it will automatically adjust the speed to the car in front until the object clears your path then it speeds back up to set speed.
D07-11 A car at away point cut me off and I felt like the car wasn't slowing down fast enough.
D07-16 It was comfortable right away.
D07-21 No
D07-38 No answer
D07-43 No

D08-3 You know how regular cruise control, you set the speed and if you have to slow down you hit the brakes and it turns off. This one automatically slows down if you have to, then speeds back up automatically.
D08-11 No answer
D08-21 Yes. On curves, even if there wasn't a car in front of me it would pick up a car on the side and slow down. Also, when driving less than the set speed for awhile, it is surprising to suddenly speed up.
D08-31 Add a light to tell when you are going slower than the speed you set it at.
D08-38 The off/on button. I don't know why it is needed.
D08-40 ACC, If there was no added cost. Otherwise, no system.

D09-3 It is a cruise control that changes its speed based on the car's speed in front of you
D09-7 Cruise control is faster than ACC because a lot of times I deactivate CC and go on manual mode
D09-11 1. When turning at high speeds – sometimes the sensor don't detect the car in front because of the angle. 2. When I see cars that are at full stop and I'm still running at more than 40mph. 3. Stop and go traffic
D09-16 3 hours of using the system
D09-19 I understand the limits of the ACC
D09-21 One time when the sunlight directly hit the sensor it malfunctioned
D09-26 I'm already comfortable w/ it
D09-30 These are base on light traffic condition
D09-31 1. If the system could also detect other cars on the road not just the car in front. 2. Option level on aggressiveness of the system
D09-38 If the sensors decrease the speed as it senses lesser of the vehicle in front vice-versa. This will be useful for shifting lanes and passing vehicles
D09-43 No

D10-3 The system uses a laser to measure the distance between your car and the one ahead of it. It then uses braking action to keep the specified distance between your car and the other car constant. The driver can set the maximum speed and trailing distance of the cruise control. As with any cruise control a slight tap of the brake or accelerator will disengage the system
D10-11 Yes. When the traffic ahead of my vehicle had stopped rapidly.
D10-16 15 minutes
D10-21 Yes. On sharp turns it would lose contact with the vehicle ahead and try to accelerate to cruise speed. The reaction time when a vehicle pulls in front of the vehicle is too slow.
D10-31 A display for the cruise control mounted higher on the dash so it is easier to see
D10-38 No answer
D10-43 The display is mounted too low on the dash. It did distract me look down to set the speed.

11-3 Set max cruise speed and adjusts it proportionally to maintain one of 3 desired distances from car in front of you. If car is far enough in front or there is no car in front cruise speed will attain set maximum
11-11 yes, approaching traffic jams, if someone cut in front of me, off ramps, or around curves in a road
11-16 A day
11-21 No
11-31 Not sure
11-38 Nothing
11-43 Not really

12-1 20 +years depending on vehicle
12-2 Yes, prior to this test I was only aware of them
12-3 Using a radar LIDAR detection system it senses the proximity of a vehicle in front of you and keeps your vehicle at a predetermined distance slowing or speeding your vehicle depending on the speed of the other vehicle up to the set speed of the ACC system
12-5 ACC brings with it potential man hazards. i.e. overconfidence and less awareness of your surroundings
12-11 Yes, occasionally the ACC system would race the vehicle toward traffic not giving a sign that it would slow until the distance became uncomfortable; when traffic would come to a quick stop ahead; when a vehicle pulled in front from an adjacent lane
12-16 I became comfortable a day or two into using it. My overall comfort with its idiosyncrasies took several more days.
12-21 On a couple of occasions it seemed to lose contact with the vehicle in front and began to surge forward
12-27 N/A
12-29 ?
12-31 I would add a package of features that increase the systems perception of the traffic around and improve its intelligence in handling/managing it. It would also have more finesse, detecting and reacting subtly to the changes in speed of the traffic ahead. It

would be best if the system only ever needed to perform emergency braking in an actual emergency. It would also be nice if it would gradually increase speed once a vehicle moves away by following its speed change or at least a mall transition as the other vehicle begins to increase speed 12-38 No answer 12-43 Only if I relied on it too heavily. Due to traffic pulling in front of the FX or traffic slowing rapidly I had to make sure I monitored the distance
Cooperative Adaptive Cruise Control Survey D01-1 The CACC system can be used when driving with another car. It works like a regular cruse control and allows automatic adjustment of the following distance relative to the car ahead of you, with a maximum speed that you set via the cruise control. The vehicle automatically slows down and speeds up to stay with the speed of traffic. D01-10 I did disengage the system once or twice when driving when the vehicle I was following braked suddenly. I could see that traffic would come close to a stop. D01-14 fairly quickly, in 1 drive (30 minutes) D01-19 I found the acceleration to be much more jerky/abrupt and not as smooth as the ACC system. D01-27 Yes, ACC—the following distances are similar to what I usually keep when driving manually. The CACC felt a little too close. D01-32 I would add one more distance setting to be slightly longer than the current maximum distance and eliminate the closest distance setting. D01-41 I would remove the closest distance setting, because I was not comfortable driving that close to the vehicle ahead of me. D01-45 NO D02-1 The system uses ACC with the added feature of communication between vehicles. A following distance (time) gap is set by the trailing car of a two car set. The forward car transmits speed information to the rear car. As the forward car slows or speeds up, the communication allows the rear car to maintain the gap during transients without significant delay in response. D02-10 Short gap, rapidly slowing traffic D02-14 One to two days D02-19 NO D02-27 Yes, I preferred the gap flexibility of the CACC system. Although, the driving experience was more contrived. D02-32 No ideas specific to CACC. D02-41 No suggestions. D02-45 NO D03-1 CACC is an enhanced safety feature of ACC. It requires a wireless connection between the computer systems controlling the operation of the leading car and the car behind. The response of the car following is slightly smoother and seemed to me more timely at closest following distance than with ACC.

D03-10 Yes, when cars would cut in front when the following distance was set to closest. In this situation, I wasn't sure that the ACC will kick-in in time to avoid impact.
D03-14 Almost instantaneously once I got used to the ACC.
D03-19 Not in an unpleasant manner.
D03-27 Yes, probably the CACC – it seemed to me to start braking more promptly to maintain the following distance—this observation is based on the very limited experience with the system. More time would have given more information by exposing me to probably more situations.
D03-32 Perhaps adjusting the feature to work at stop and go traffic conditions.
D03-41 not applicable
DO3-45 NO

D04-1 The ACC is a type of cruise control where you can not only set the speed for your car, but you can also determine the distance (generally 1-, 2-, or 3- car lengths) from which you will remain behind any vehicle in front of your car, and your car adapts itself to maintain that distance, regardless of the speed you've set. The CACC does the same, only with shorter set-distance ranges, and an extra set distance to select.
D04-10 i) In heavy traffic that slowed down <40 mph; ii) exiting the highway.
D04-14 one day
D04-19 i) reaction—that the vehicle responded so quickly and that you could feel the response, which is comforting to know that it's working; ii) that the system stopped itself when driving on a wet highway (not raining).
D04-27 Yes, CACC—appreciated the shorter distances and more options for distances.
D04-32 A separate reading for actual speed (digital) versus set speed.
D04-41 not applicable
D04-45 NO

D05-1 A user can set the amount of space between you and the car in front to maintain during your drive. The system will either slow or speed up based on your cruise control speed. It is very cool!
D05-10 When I set the distance to the shortest distance, it was too close for my comfort so I would use the brakes before the system.
D05-14 Not long. It was very easy to use.
D05-19 No, loved the system.
D05-27 Yes, I did prefer the ACC system because of the distance settings. The shortest setting on the CACC was too close for me. The ACC seemed to have distance settings that I would use.
D05-32 Illuminate the cruise control settings on the steering column. If you are not used to the system, it is difficult to see at night or in darker conditions. Also, the short distance setting is a little too close for my comfort.
D05-41 I would remove the shortest distance method – the car in front would be too close for my comfort level.
O5-45 NO, The system worked as I had hoped. I really love the fact that it would maintain a proper distance between the vehicles.

D06-1 It is an automatic speed control system between two cars that uses radio to communicate speed and distance information to maintain distance and speed.
D06-10 Acceleration at times was jerky. Also sudden stops made me more willing to brake.
D06-14 After the initial introduction about one hour.
D06-19 No.
D06-27 Yes, I like the faster brake response of the CACC but wish the acceleration was more smooth.
D06-32 Distance display.
D06-41 There were no feature/display methods I would want removed.
D06-45 no answer.

D08-1 You set the cruise control and there's a sensor that keeps you at a certain distance from the car in front. The idea is to keep you close but keep traffic flowing, so there's no back up.
D08-10 Yes, when cars cut in and the speed decreased quickly. It could make you lose control if not ready for it.
D08-14 A few trips
D08-19 See answer to question 10
D08-27 Yes, you set closer to the vehicles and less people cutting in front.
D08-32 Add a way to set the cruise control speed at the speed you are going. It would be like setting the speed, but able to do it after the speed has been set.
D08-41 None
D08-45 None

D09-1 It is a modified version of ACC which is more advance. It directly communicates w/ the car in front through a dedicated signal.
D09-10 Two incidents. Both incidents the vehicle I was driving was not able to communicate w/ the car in front.
D09-14 30 minutes
D09-17 Can't say cause I was just following the lead car
D09-19 Yes. When it failed to communicate to the lead car
D09-24 Already comfortable
D09-27 yes, CACC the gaps are shorter
D09-32 If it can detect other vehicles aside from the one in front
D09-34 Already comfortable
D09-41 Same as my answer on ACC
D09-44 I don't understand the question
D09-45 None that I can remember

D10-1 The system works like a normal a cruise control except it has the capability to adjust to changing traffic speed conditions. The driver can select the maximum speed for the vehicle and how close they wish to follow the traffic ahead. The vehicle will then accelerate or brake to adjust to the current traffic speed.
D10-10 When another car moved in between my vehicle and the chase vehicle I had to disengage the system. The abruptness of the brakes action of the CACC vehicle was a bit

uncomfortable
D10-14 2 Minutes
D10-19 The abruptness of acceleration or braking did surprise me
D10-27 Yes. The CACC system allowed for greater accuracy and faster response times
D10-32 No answer
D10-41 No answer
D10-45 No answer

12-1 CACC controls the vehicle speed by sensing the vehicle in front acting as a space cushion. It uses a radar unit to detect vehicles in front and adjusts the speed down to match or up until it reaches your max sitting. CACC also reads data from the vehicle in front about the status of the brakes and engine to assist in early detection of speed variations
12-10 Yes. Whole in stop and go traffic; When traffic in front stopped abruptly
12-14 After becoming familiar with ACC it only took a brief familiarization with the CACC to become comfortable
12-19 No
12-27 Yes, CACC, I prefer the ability to close the following gap. It would be nice if it could get closer and had the option of the middle distance option on the factory system
12-32 Smoothing out the speed transition
12-41 Not sure I would actually want to remove something
12-45 No

Chapter 9: Effects of Local Traffic Conditions on ACC and CACC Usage

The collection of detailed in-vehicle data about drivers' usage of ACC and CACC on highways that were already instrumented to provide archival records of traffic conditions provided a unique opportunity to identify the specific relationships between traffic conditions and ACC usage. This Chapter describes the technical approach to match these different data sources with each other and the results of the analysis and their broader implications for ACC usage.

9.1 Generating data: C/ACC-vehicle and PeMS

This section discusses the steps involved in the synchronization of two data sources. Section 9.1.1 describes both inputs, section 9.1.2 the method that was used and section 9.1.3 presents (a visualization of) the output.

9.1.1 Inputs

Inherent to the goal of synchronization is the input of multiple data sources.

Source I (C/ACC vehicles)

The vehicle data acquisition systems were developed and verified under Task Order 6202, and the specific data elements that were recorded are described in the final report on TO 6202.

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 ten years from freeways throughout California. It shows the traffic flow, occupancy and, when possible, traffic speed measured directly through detector loops that are placed on the highway.

Detector loops

PeMS as a whole contains data from more than 26,000 detector loops divided over 8,100 detector stations [PeMS, n.d.], installed between 500 and 800 meters apart. [Varaiya, 2001] This, however, varies considerably depending on the respective location. Appendix 0 contains a map of the placement of detector stations throughout Caltrans District 4, where the ACC experiments were conducted.

The detector loops aggregate traffic measurements, usually over a 30-second interval. Most detectors in District 4, which covers the C/ACC driving area, are double loops and therefore provide speed data. When the loop does not record speed, the result is a blank field in the data. Not all detectors work all the time. 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 Section 9.2, "9.2 Method" do a further cleaning of the data.

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 passing in that time interval. 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 shorter intervals might not "provide a sufficiently large window to capture the cause-and-effect process involved". Figure 9.31 presents the relationship between traffic speed and different traffic flow samples.

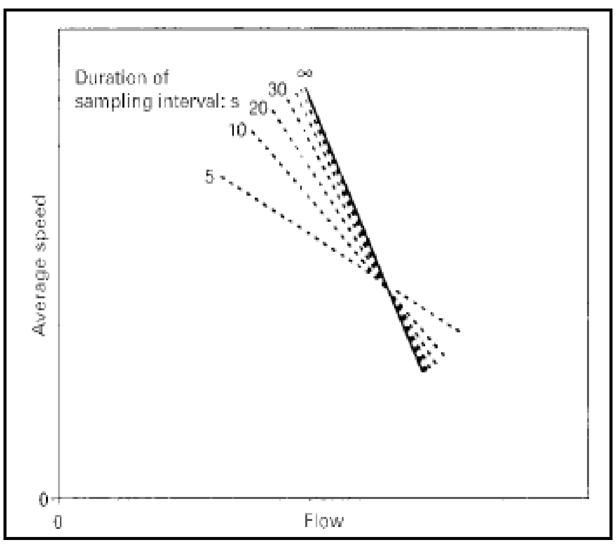

Figure 9.31: Effect of aggregate interval on flow accuracy [Wright and Lupton, 2001]

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, 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]

Data organization

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

The data obtained from the PeMS database are summarized in Table 9.1.

Table 9.1 Data Obtained from PeMS

Group	*Name*	*Description*
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)

9.2 Method

This section illustrates the synchronization of the vehicle data and the PeMS data and the modification of the results.

9.2.1 Synchronization

Figure 9. shows the stages of this process. The first source is the vehicle data and Sources 2 and 3 are the detector station metadata and detector station data, respectively. The top three boxes of Figure 9. represent these sources.

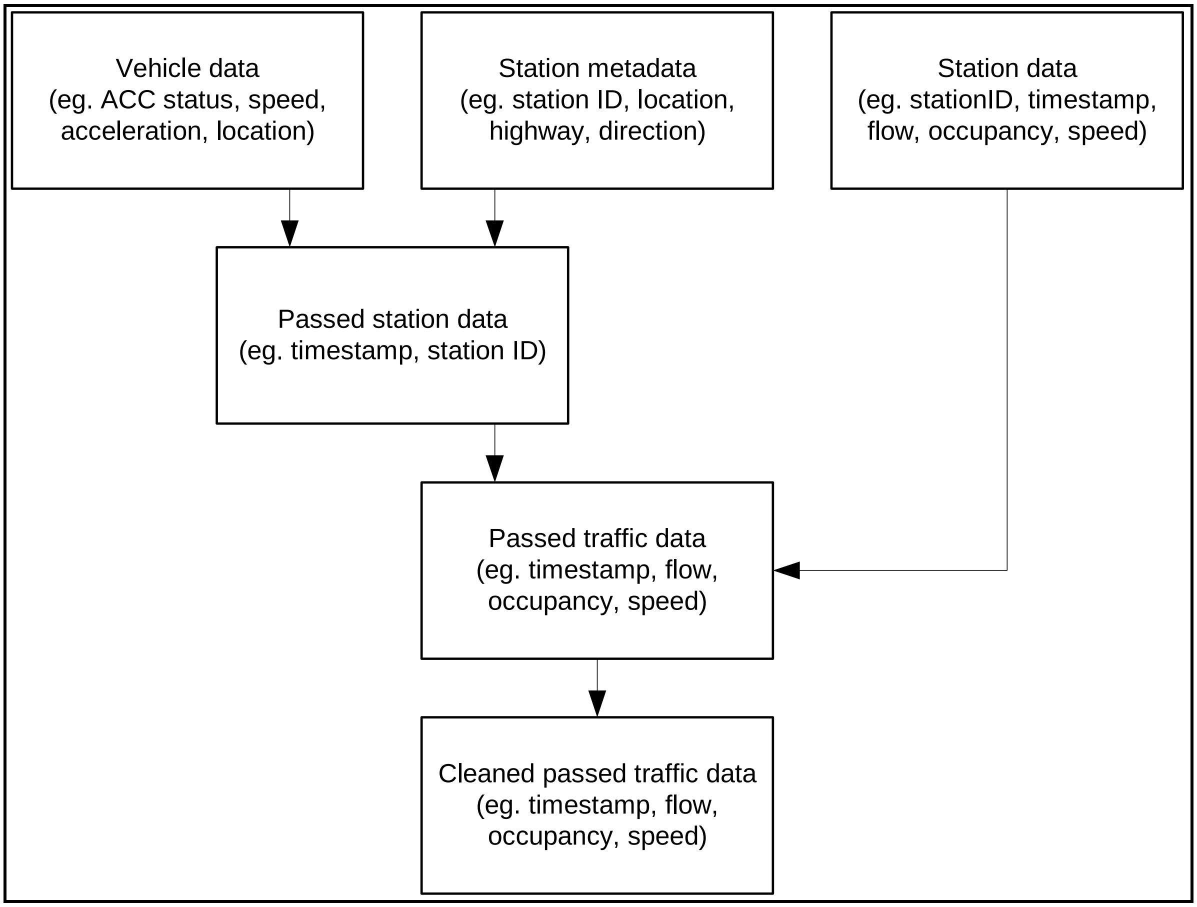

Figure 9.2: The synchronization & cleaning process

Data From Passed Detector Stations

Passed detector station data is created in the synchronization of vehicle data and detector 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 meter radius.[4] This resulting list contains passing time, detector station ID and several other location parameters.

Passed traffic data

With a list per trip from the passed detector 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.

[4] 14 meters is about the distance of going both 0.0001-degree in latitude and 0.0001-degree in longitude.

9.2.2 Data modification

The traffic data files contain errors that should be removed prior to any analysis. Table 9.2 lists all known errors and Table 9.4 explains the arguments for excluding these values. The script removes data with any of these errors and creates a new file with 'clean' data.

Table 9.2: Errors in the traffic data[5]

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 of Table 9.2 shows the percentage of the total removed data because of errors. Note that this is cumulative, so data removed because of the flow are not removed again because of the speed. Stations found in the other direction are, unlike the rest, a result of the synchronization script and is not an error in the traffic data.

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

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

[5] 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.

Table 9.3 Arguments for excluding data samples in the data cleaning process

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 analyze, 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.]

In addition, the script combines data from the different lanes to create 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, we did 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 of all the lanes and a single numerical description of the variations across 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.

9.2.3 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 are recorded at 20 Hz and can be considered continuous. Because of the differences between both data sets, choices have to be made regarding the synchronization 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 was 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 makes interpolation only accurate enough on a limited portion of the highway network. Measuring C/ACC usage related to traffic data transitions, from one detector to another, for these limited cases, is performed in Section 9.4.6.

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 detector station.

9.2.4 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 are 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 9.. 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 9. 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 is not static in relation to the detector station.

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

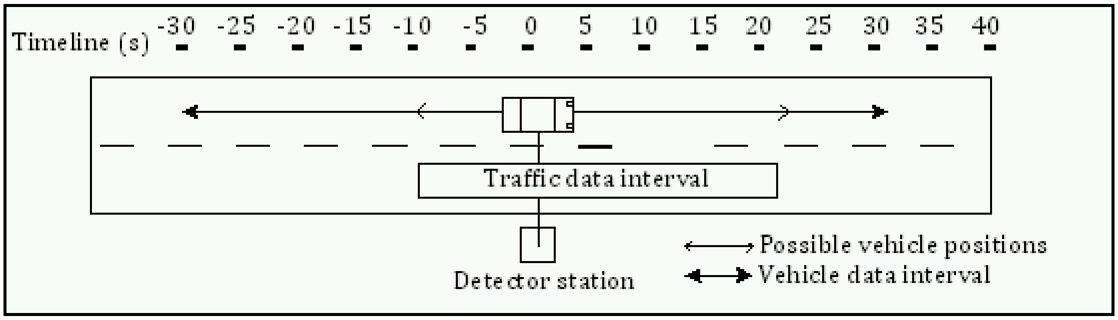

Figure 9.3: Temporal data intervals

9.3 Data Outputs

After generating and modifying the data, it can be visualized and assessed in a number of ways. Section 0 describes the structure of the data. The visualizations in Sections 0 and 0 present explanations of the content.

9.3.1 Dataset

The software found an average of 17 loops with healthy data per C/ACC trip. The average time between the first and the last found detector was 29.8 minutes, which means that there is an average of 1.45 minutes between consecutive found detector loops.

shows the distribution of the times and distances between consecutive healthy and passed detector loops.

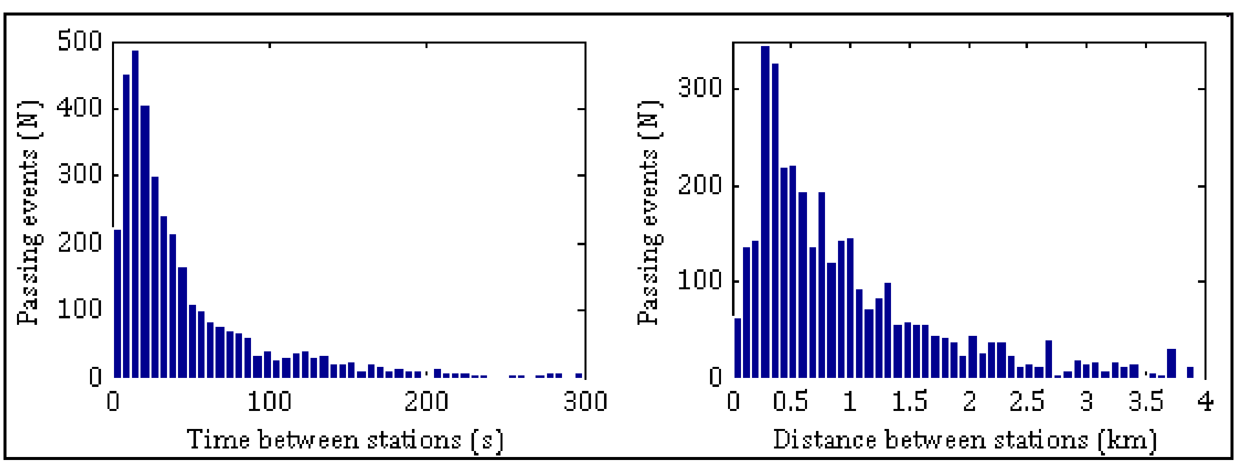

Figure 9.4: Distribution of "between times and distances".[6]

Next to the placement of the detector stations, there is also a high variability between the vehicle speed and the traffic speed and the traffic speed across different lanes. Figure 9.32 shows these differences in a histogram. The lines represent the distribution of the standard deviations of (i) the different lanes at one detector station and (ii) the traffic speed and the vehicle speed.

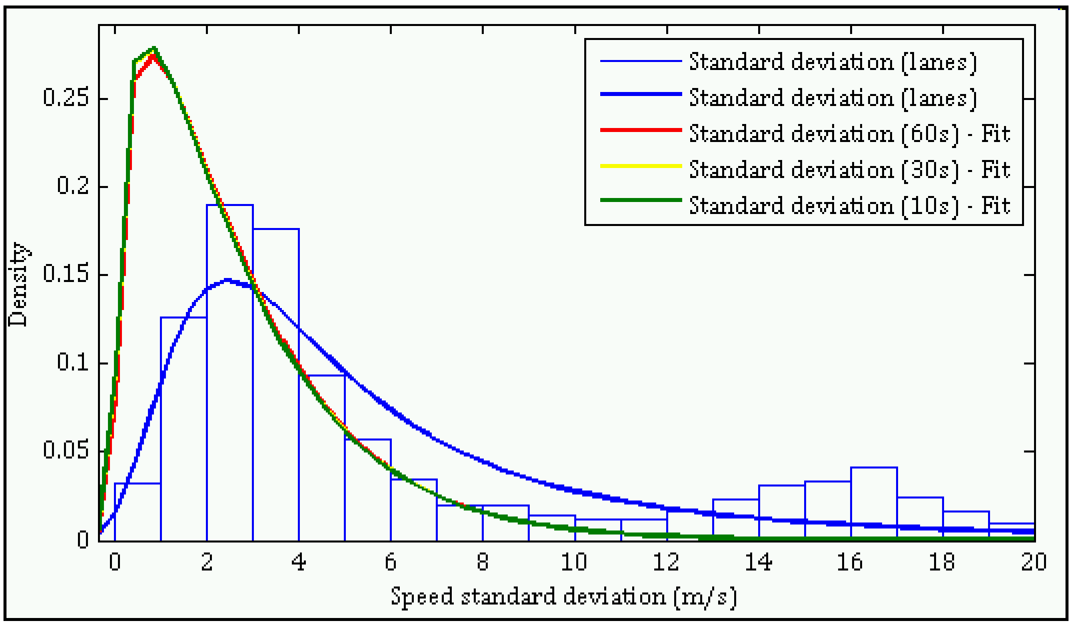

Figure 9.32: Standard deviation of speed between lanes and between vehicle and traffic.

"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 three distributions show a negligible influence of the temporal fluctuations of traffic on the speed difference between the average traffic and the vehicle. The major cause of traffic moving at a different pace than the C/ACC vehicle is however the difference between lanes. The histogram shows the standard deviation between lanes in the same figure. Interesting is the large sample of speed differences at around 15 m/s. The presence of HOV (high occupancy vehicle) 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. Fluctuations between lanes and temporal fluctuations on a lane could describe a traffic state better than an individual vehicle. The following subsection provides a microscopic visualization of the traffic conditions along a single trip.

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

9.3.2 Microscopic visualization

Figure 9.33 presents a plot usable for microscopic data analysis.

Figure 9.6 represents trip 307 by driver 3 in the silver (ACC) vehicle. The top plot shows four 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 were 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.[7] 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 the 41 points of measurement. It is interesting to notice 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 those changes by the system. 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 section shows another way of more efficiently visualizing the data, namely macroscopically.

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

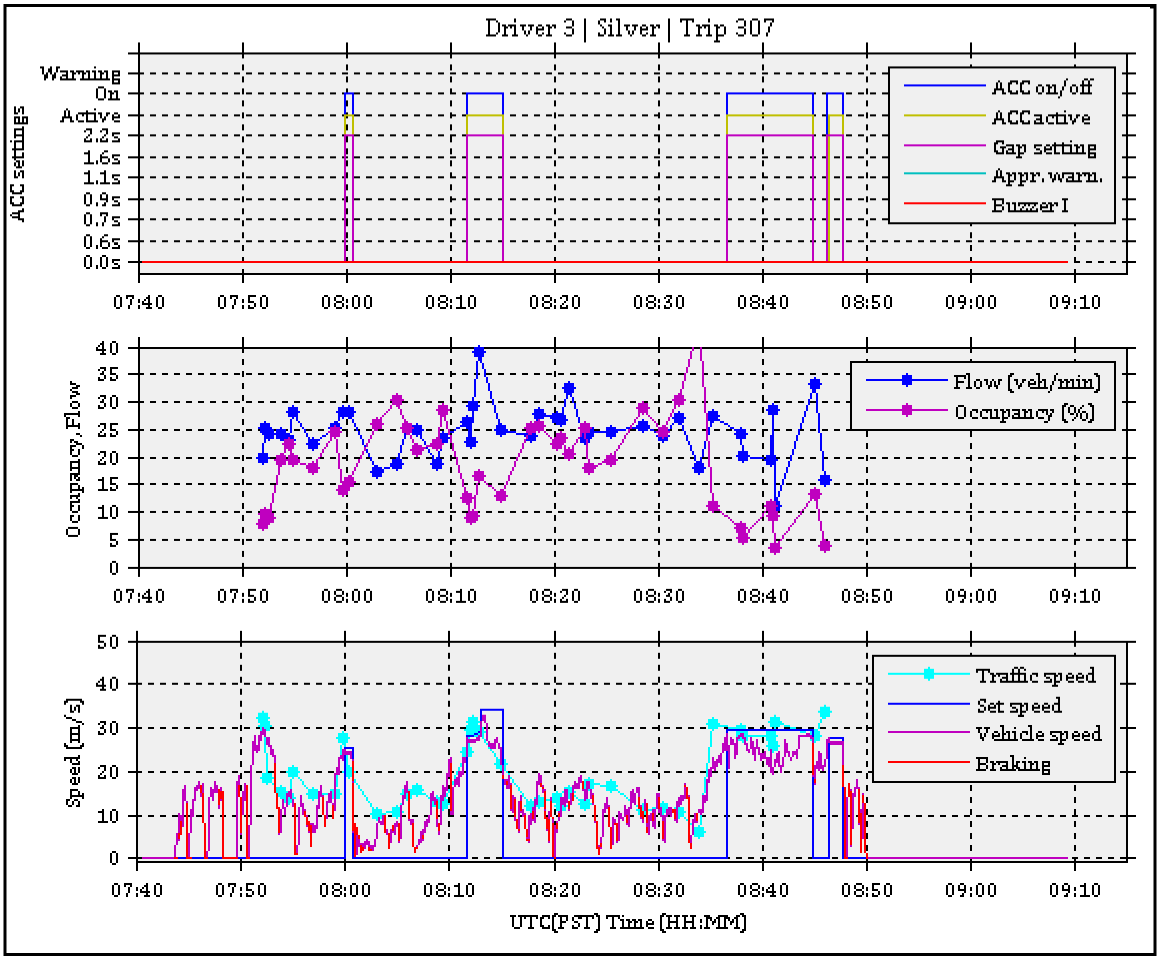

Figure 9.33: Details of trip 307

9.3.3 Macroscopic visualization

In this macroscopic visualization, the data from all passed detectors from all trips are combined in the fundamental diagram of traffic flow, Figure 9.34. 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. Vehicle speeds below 7 m/s are excluded.

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 visualizations and others, several types of analyses are possible with this combination of C/ACC data and traffic data. Section 9.4 reports the results of some of those analyses.

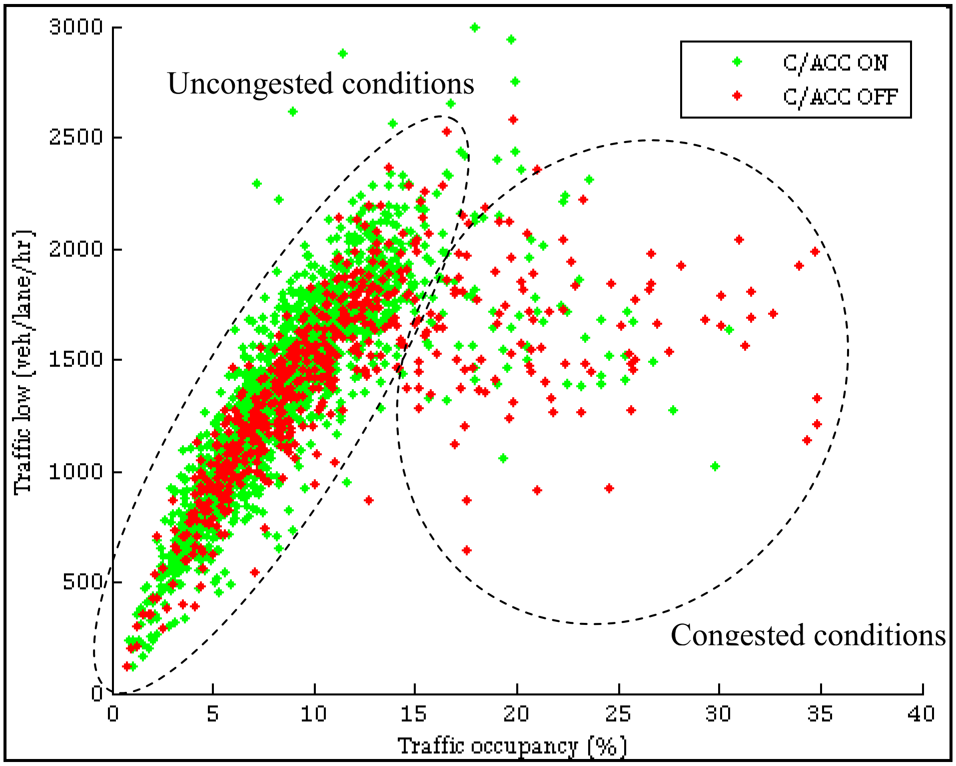

Figure 9.34: C/ACC usage under different traffic conditions

9.4 Analyzing Data: Drivers' Use of C/ACC

As shown in the last section, 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 behavior related to the traffic conditions. Extrapolating this to larger numbers of C/ACC users on the highway, it can give good predictions of the total effect of users under different conditions. In addition, one can look at the effect of traffic condition transitions in the usage of C/ACC. To conclude the analysis, the quantitative findings are compared with the results of the questionnaires the participants filled in.

9.4.1 C/ACC usage related to traffic conditions

The dataset is divided into several layers to learn the underlying reasons for the C/ACC usage in general. The data are then subdivided to explore differences in usage between ACC and CACC and between drivers.

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 about C/ACC usage in those conditions. Figure 9.35 shows such a plot.

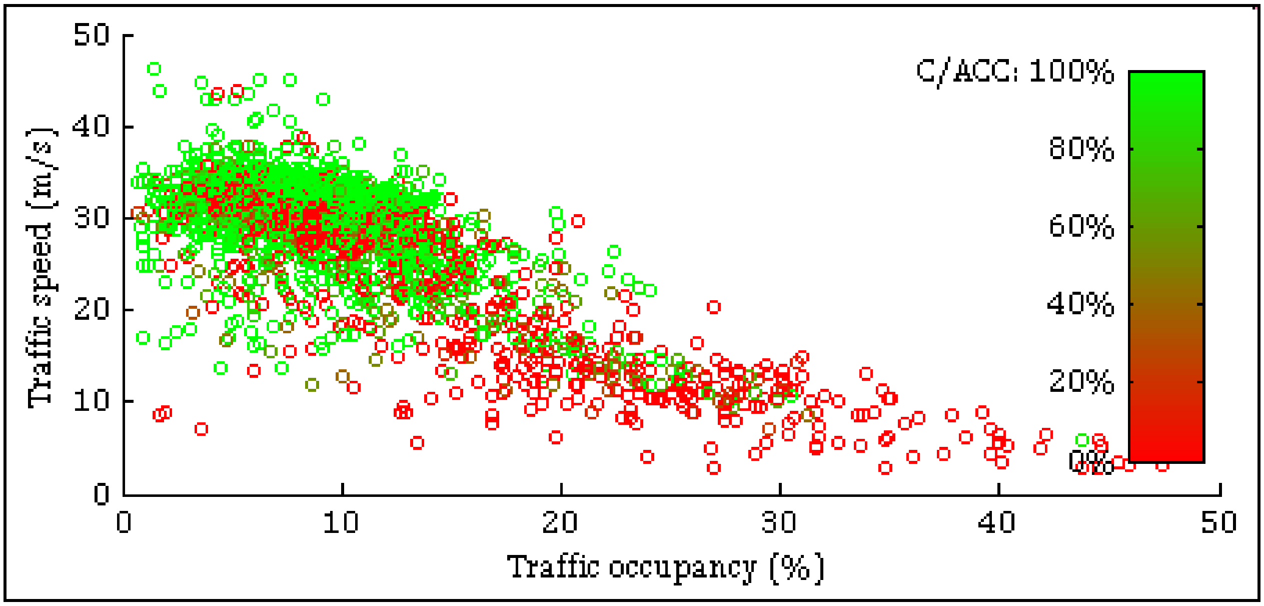

Figure 9.35: C/ACC usage during the 60-second interval in reported traffic conditions.

This figure shows average C/ACC usage during 60-second intervals. By far most of the data are 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 visualization reveals however, much noise, mainly caused by differences in (commutes of) drivers and inaccuracies in the traffic data. Because analyzing all passing events individually does not allow for good numerical analysis, the next section aggregates over different traffic condition intervals and visualizes general trends in the dataset.

9.4.2 Trends in C/ACC usage

Figure 9.36 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, detector passing events, available.

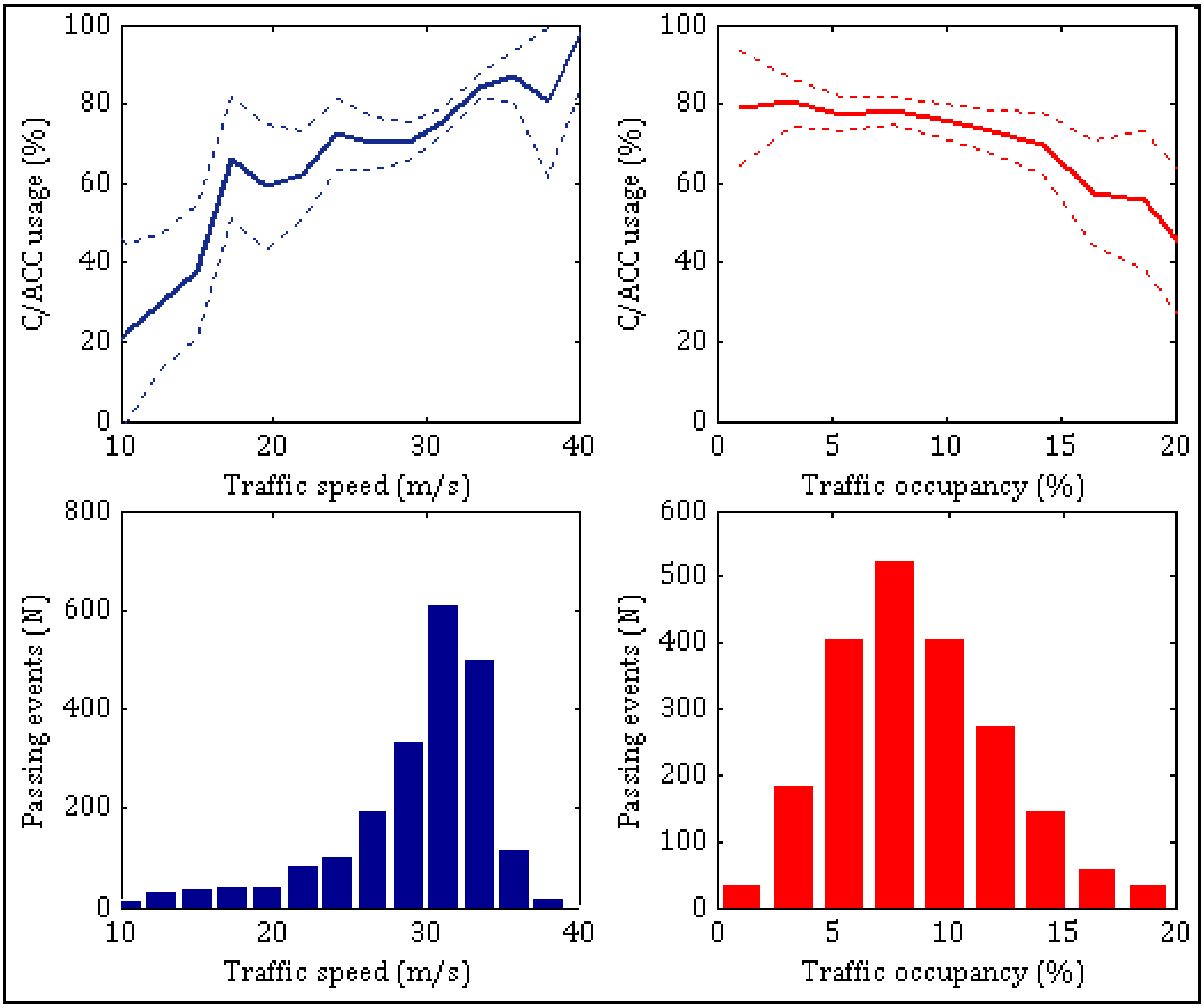

Figure 9.36: Relations between traffic conditions and C/ACC usage

Trends of C/ACC usage in different traffic speeds and different traffic occupancies are clearly visible. In light traffic, the 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 limited availability of data makes it impossible to analyze behaviour in those conditions. The lower plots of

Figure 9.36 show the distribution of the traffic speed and occupancy measurements respectively. Note that the figure does not show speeds above 40 m/s because of questionable accuracy of the available data.

Assuming the ability of these parameters (traffic speed and occupancy) to estimate traffic conditions, one would expect a clear breaking point of C/ACC usage between two distinct conditions. The linear trend, visible in the upper plots of

Figure 9.36, would mean the situations in which users tend to turn off their C/ACC depend on factors beyond the traffic conditions alone, such as the respective driver, ACC vs. CACC etc. A multivariate analysis of variance conducted on the available variables reported significant differences in C/ACC usage depending on both the individual drivers and the different systems (ACC and CACC).

The 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 were 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 the driver itself. The F value of **Error! Reference source not found.** 9.5 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			

Table 9.4: 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 latter can be explained by the fact that every driver had distinct commutes with therefore distinct highways. Commutes are divided by "mornings" and "evenings", but there is no significant difference in the C/ACC usage between those two types of commutes.

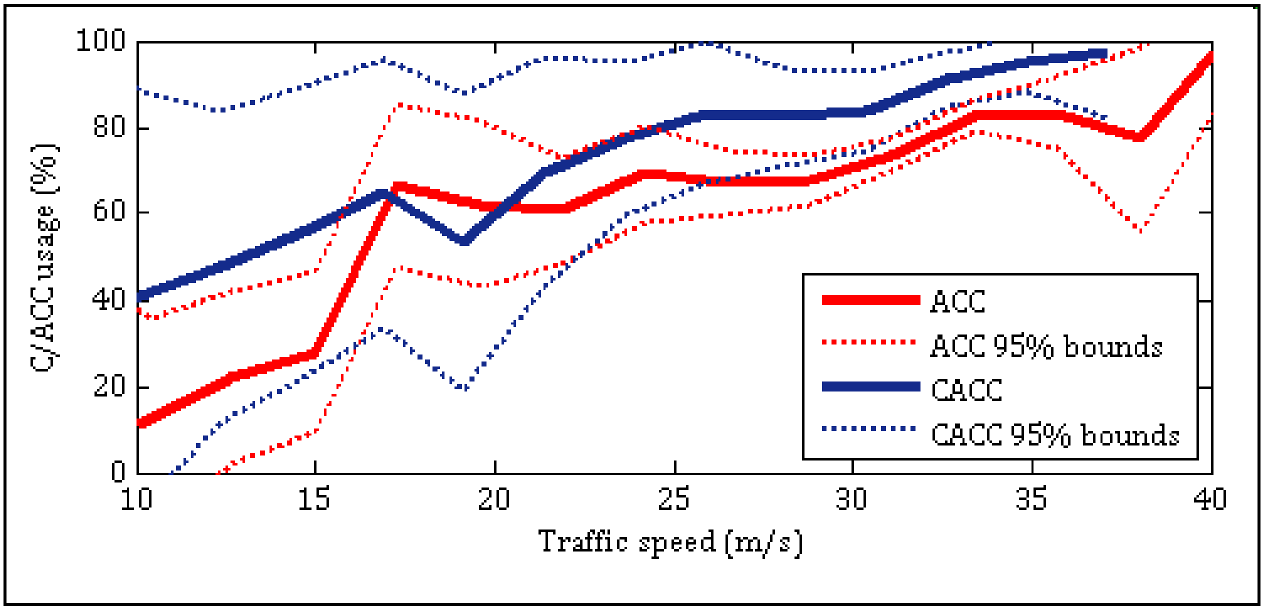

Figure 9.37: Differences between ACC and CACC usage

Figure 9.37 presents the difference between ACC and CACC usage percentage 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 amount of data available at the lower speeds cause a very broad 95% confidence zone. In fact, there is a statistically significant difference in ACC and CACC usage at only a few higher speed 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 experimental protocol required 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 Figure 9.11.

(ii) A PATH employee had to be in the passenger's seat next to the driver while driving all CACC trips. This might influence the overall usage of the system.

(iii) The drivers had new gap settings to experiment with while driving CACC.

(iv) Due to the nature of CACC, the drivers had to follow the confederate ACC vehicle throughout the trip. In addition, the gap settings on the CACC make the risk of cut-ins smaller. 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 limitations in the data, it is also possible that both CACC and ACC result in the same behavior and that CACC usage does not have a significant trend with respect to the traffic conditions.

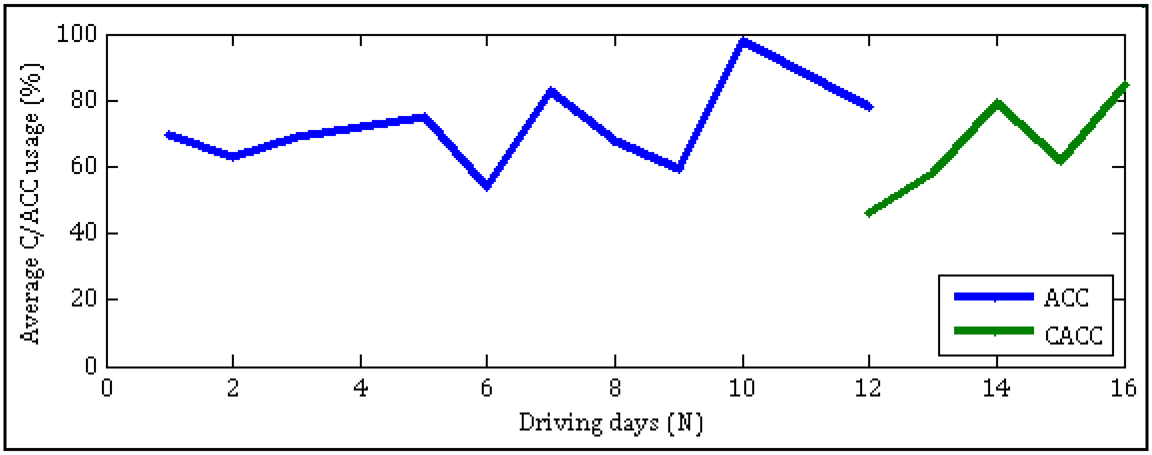

Figure 9.11 Average Usage of C/ACC by Day of Experimental Protocol

9.4.4 Trends in drivers

Figure 9.12 shows the difference in C/ACC usage among drivers in a boxplot. The black dot represents the average C/ACC usage over all trips of each driver, while 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 open blue circles are outliers.

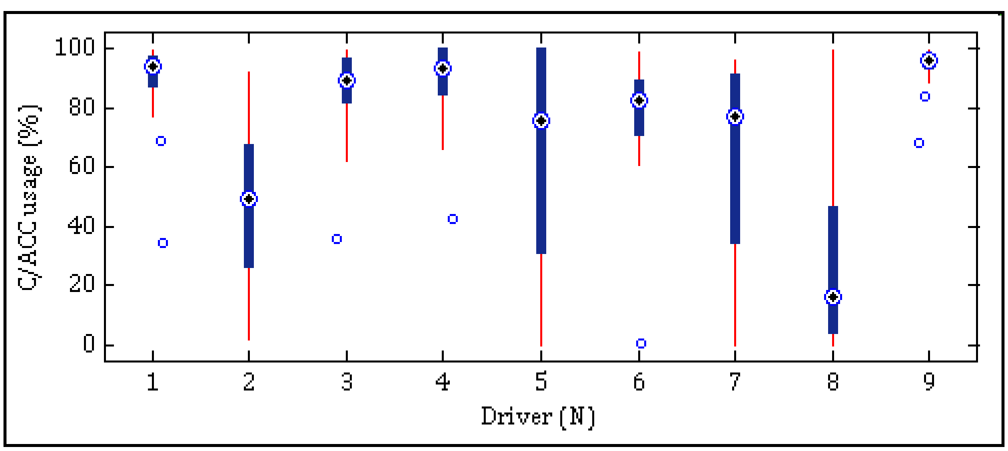

Figure 9.12: Average and variation of C/ACC usage on a per trip basis

Note the small variation across 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 among trips of the same driver, makes it difficult to see a clear pattern in reactions to traffic conditions (Figure).

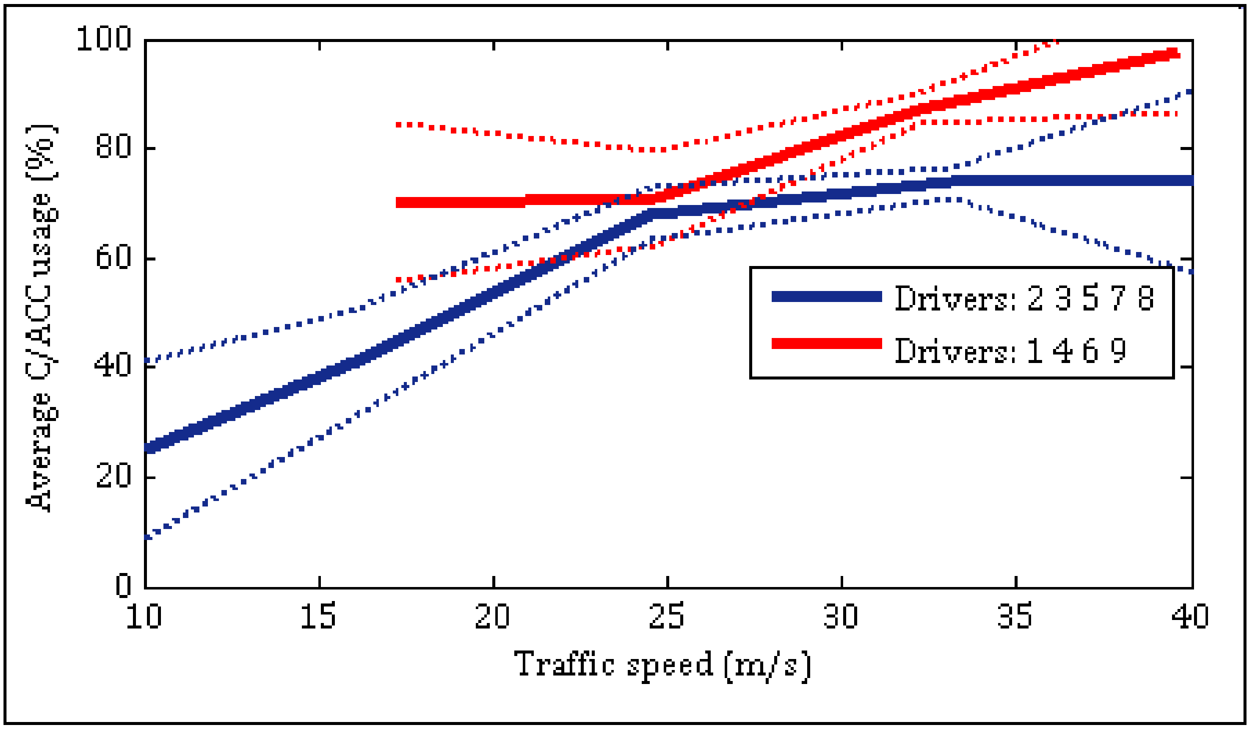

Figure 9.13: C/ACC by different drivers with 95% confidence interval

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

It is interesting to see not only the difference in average usage, but also the different reactions of the drivers to 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 reaching 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 limited 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, analyzed in the next section.

9.4.5 Gap Selection Versus Traffic Conditions

Drivers of the ACC system can choose among 1.1, 1.6 and 2.2 second gaps; with the CACC system, they can choose among 0.6, 0.7, 0.9 and 1.1 seconds. The choice of gap settings may be dependent on two distinct uses of C/ACC, the speed regulation mode and car following mode. Note that only in car following does the driver actively experience the gap setting, so the analyses are based on data while car following. Since the data acquisition computer does not store a single variable to make a distinction between these modes, several assumptions lie behind the partition.

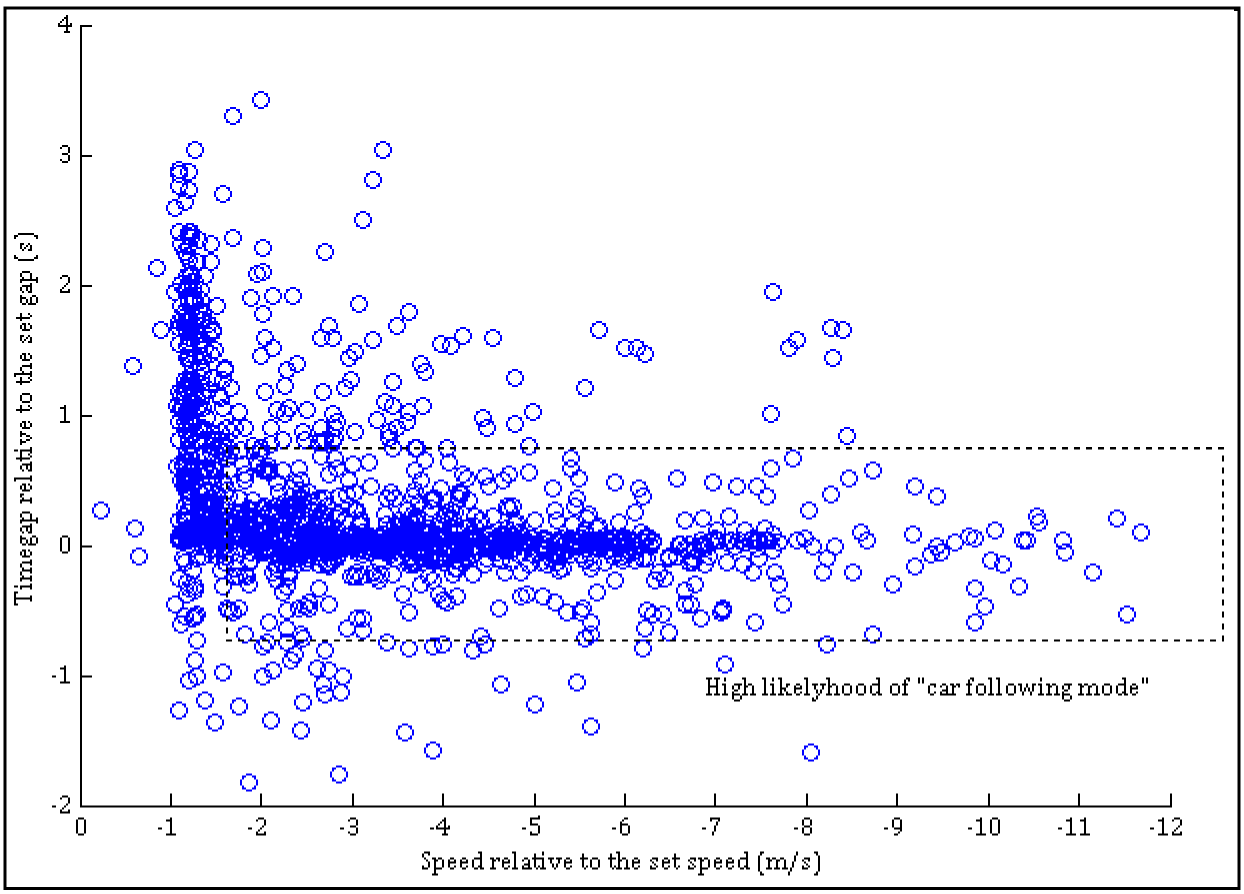

Figure 9.14: Mode identification based on speed and time gap relative to settings

The car following versus speed regulation 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 be regulated based on the maximum given speed. However, if the time gap 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 9.14 shows these two measurements for "mode identification".

It is interesting 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 dashed rectangle as "car following mode".

Gap settings in ACC

Figure 9.15 contains a plot of the chosen gap setting relative to the traffic conditions for the ACC system.

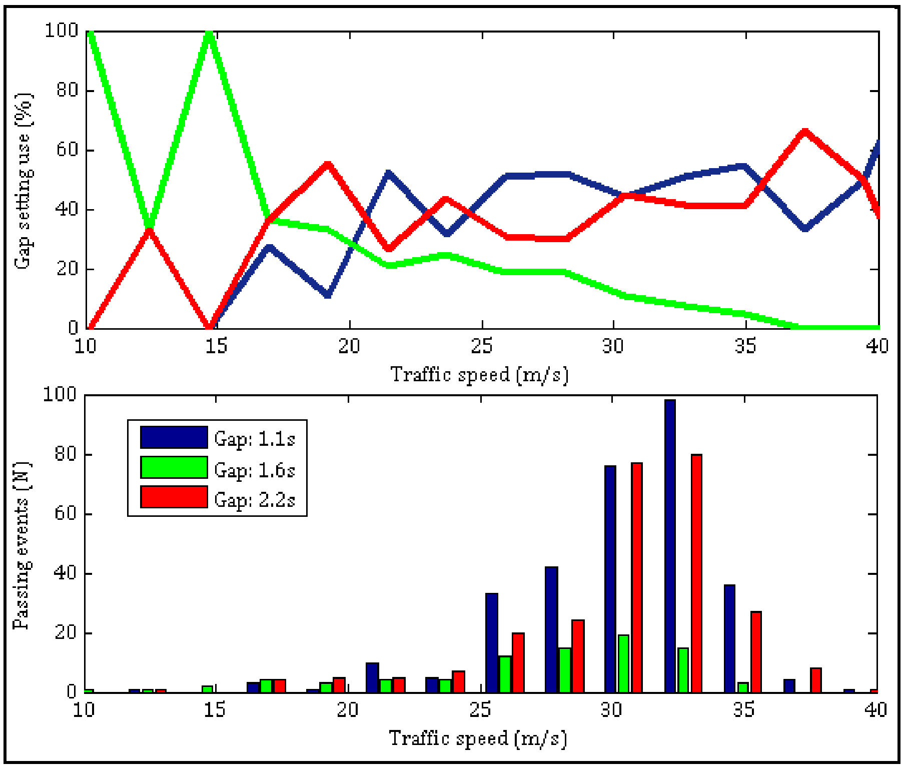

Figure 9.15: Gap setting of ACC system versus traffic conditions[8]

The decline in the usage of the "middle" setting, 1.6s, is interesting, while the other settings are at about the same level throughout the range of traffic conditions. For the average driver, it means that the selection of the preferred gap settings does not relate to the traffic situation, e.g. otherwise, there would be a trend towards either the longer or the shorter setting. Figure 9.16 shows the gap usage per driver.

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

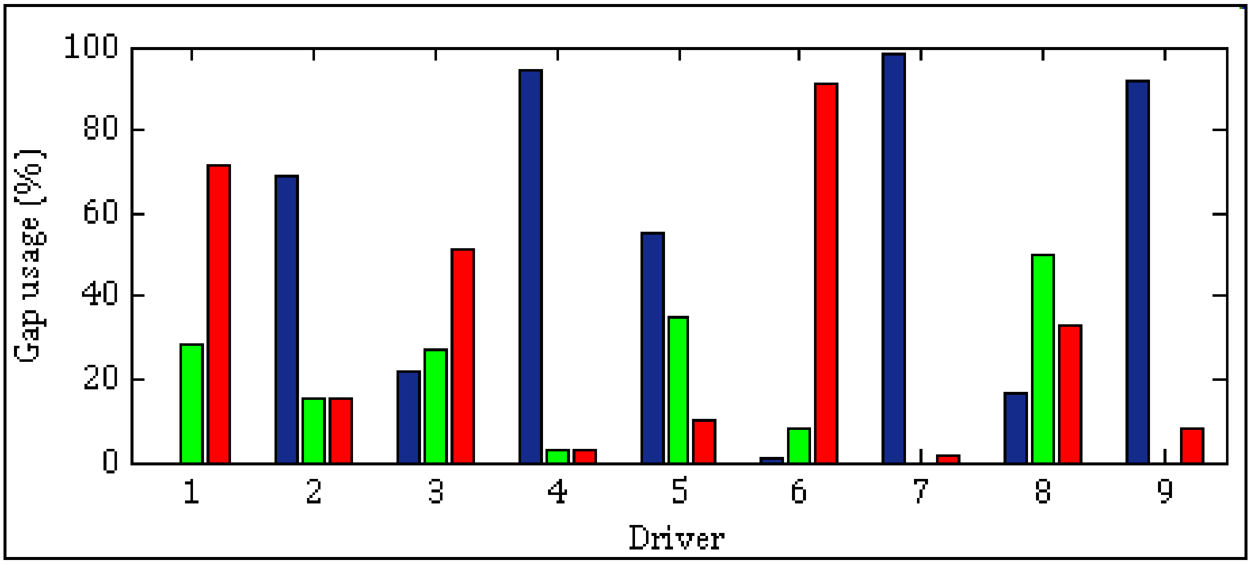

Figure 9.16: Variations Among Drivers in Selection of ACC Gap Settings

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 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 are aggregated.

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 in different traffic conditions. 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. Explanations could be:

(i) variations in 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, since Drivers 2,6,7,8 and 9 are male.

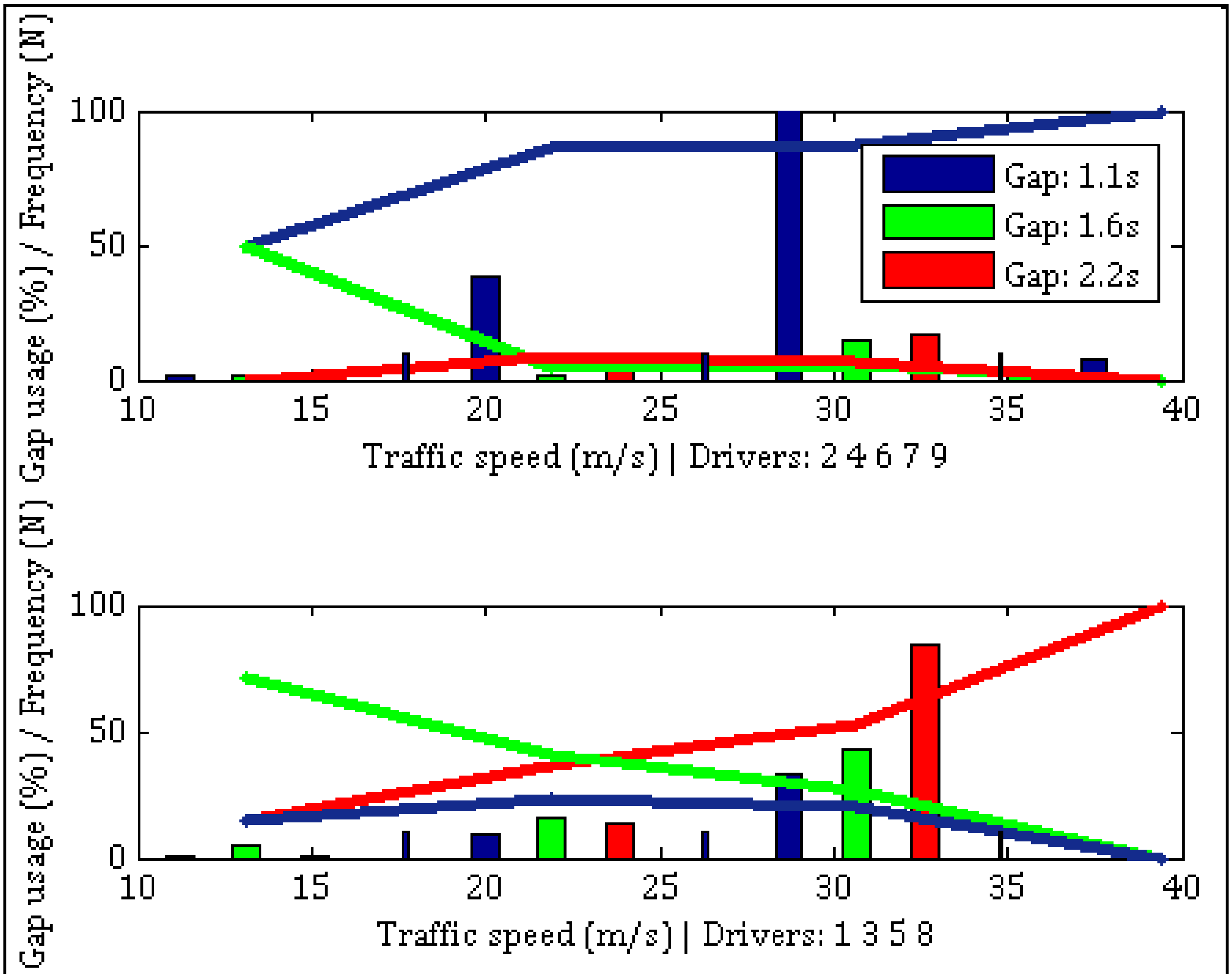

Figure 9.17: Contrasts in Gap Setting of ACC system between groups of drivers.[9]

Traffic conditions seem not to influence the average chosen gap setting of the drivers. However, a closer look at differences between drivers revealed, 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 behavior and possible predictor variables such as traffic speed, driver, and baseline gap choices showed significant differences between the set gap and drivers and between the set gap and the baseline gap. There were no significant differences between set gap and traffic speed.

Gap settings in CACC

Figure 9.18 shows CACC gap settings related to the drivers. As was the case with ACC, individual users have distinct preferences. The 0.9-second setting was "on" only two times

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

while passing a detector station in the car following mode. All drivers seem to prefer the 0.6, 0.7 or 1.1-second settings.

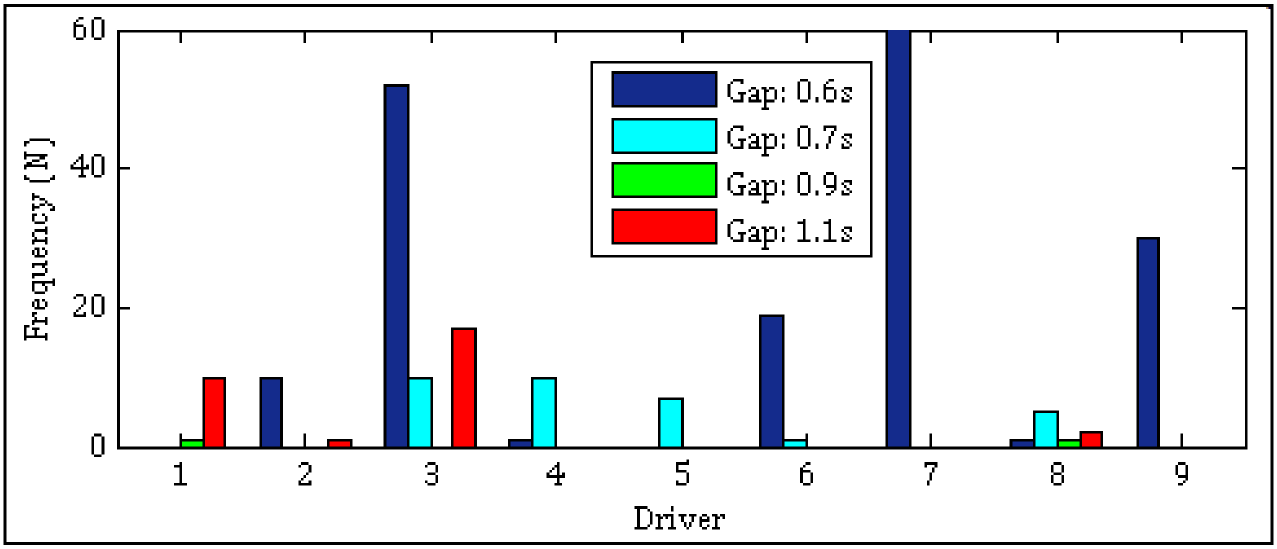

Figure 9.18: CACC gap selection by driver

Figure presents the chosen gap settings relative to the traffic conditions. A large majority of the detector passing events had the shortest setting enabled. There is no clear relationship with traffic speed. The fact that the CACC vehicle had to follow the confederate 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. CACC usage, like ACC usage, is inversely related to the traffic speed. The lack of difference between CACC and ACC usage patterns could imply that drivers stick to their original choice, and just turn the system off when that choice does not make driving more comfortable.

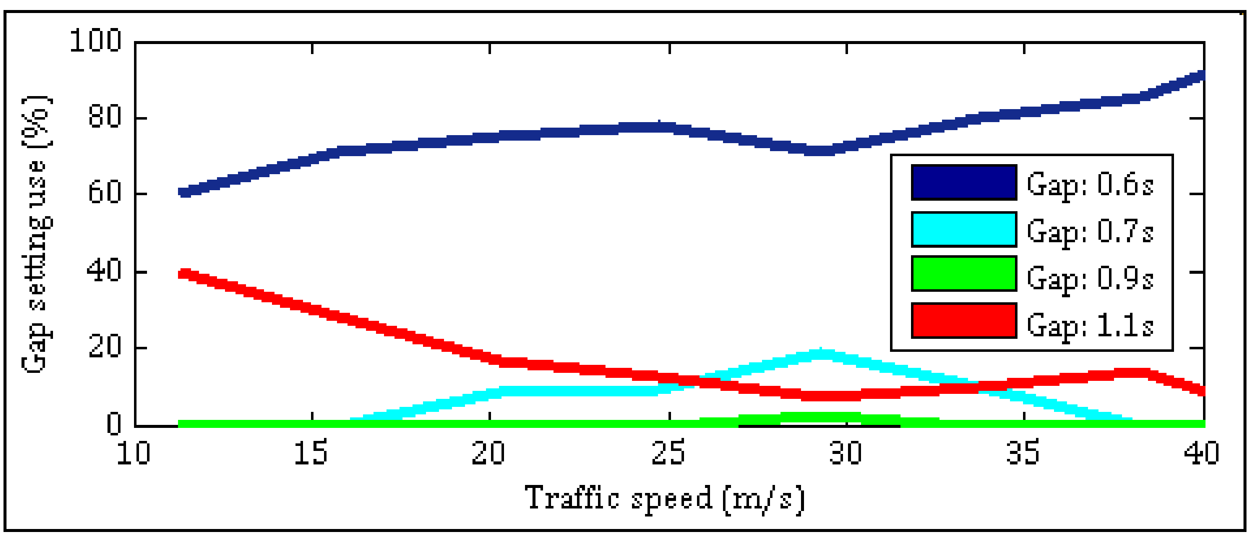

Figure 9.19: Gap settings versus traffic speed with CACC system

9.4.6 C/ACC Usage in Traffic Condition Transitions

This section analyzes the relationship between C/ACC usage and changes in traffic conditions.

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 changes 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 usage is measured as a function of traffic speed change. Table states an example of the data for cases in which traffic speed changed from 20 to 25 m/s. The data from Table would result in a data entry of "83 (33)".

Table 9.5: 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%

Table 9.7 is a transition matrix containing the transitions between traffic speeds, which shows the impact of those transitions on average C/ACC usage. Speed 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% when the traffic speed was 10.

[10] All speeds in this section are reported in meters per second (m/s).

Table 9.6: C/ACC usage at t1 (%) (Change from t0 (%))[11]

		Speed at t1 (m/s)							
		5	10	15	20	25	30	35	40
Speed at t0 (m/s)	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 . Obviously, the C/ACC usage increases when traffic is speeding up, represented in the right upper triangle, and the C/ACC usage decreases when speed is slowing down, in the left lower triangle. Traffic speeding up from 15 to 35 m/s had the consequence that C/ACC status is changed from 'off' to 'on' 70% of the time, a greater increase than when going from 25 to 35 m/s or from 30 to 35 m/s. However, this increase is solely due to the increasing likelihood that C/ACC is already active in the first place. When this is accounted for, rapid increases in traffic speed seem to have a lagging effect on C/ACC usage. An increase from 10 to 25 m/s causes C/ACC usage to rise to 17%. An increase from 15 to 25 m/s, however, causes C/ACC usage to rise to 75%, from 0% in the first case.

Traffic speed decreasing to 10 m/s, whether it started at 25, 20 or 10 m/s, 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 m/s. When drivers are in traffic that decelerates from 35 m/s, a free-flow speed, to 25, the majority leave the C/ACC "on". Starting at the same speed and decelerating 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.

9.5 Conclusions Related to Traffic Conditions

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

The combination of in-vehicle C/ACC usage data with archived infrastructure-based traffic condition data provided a unique opportunity to study the interactions between C/ACC usage and traffic conditions. The traffic condition data were only available for limited portions of the C/ACC highway drives, restricting the breadth of the conclusions that can be drawn. The two main conclusions that were apparent from the available data are:

(1) The usage of C/ACC varies significantly with the prevailing traffic speed and density. In light traffic at high speeds, the usage was in the range of 80% to 90%, but in lower speed congested traffic it was only in the range of 10% to 20%. This is in large part a consequence of the fact that the ACC system that was tested was not designed for use at lower speeds, so the results could be considerably different for a full-speed-range ACC.

(2) The selection of time gap was remarkably unaffected by traffic conditions. Most drivers developed a preference for one or two time gap settings and held to those settings regardless of the traffic conditions. If the traffic became too slow or dense for effective use of the system at the preferred gap setting, the drivers tended to switch to manual driving rather than modifying the gap setting.

An additional observation is associated with the dynamic changes in traffic conditions. When traffic is speeding up from congestion toward free flow, drivers tend to wait until they are close to the free flow speed before re-activating their ACC rather than using the ACC speed regulation capability to do the acceleration for them. When traffic is slowing down approaching a bottleneck, most drivers intervene to deactivate the system between 25 and 20 m/s. This may be associated with the limitations in the ACC sensor range and braking effort, which require drivers to apply the brakes manually for all but the gentlest traffic slowdowns.

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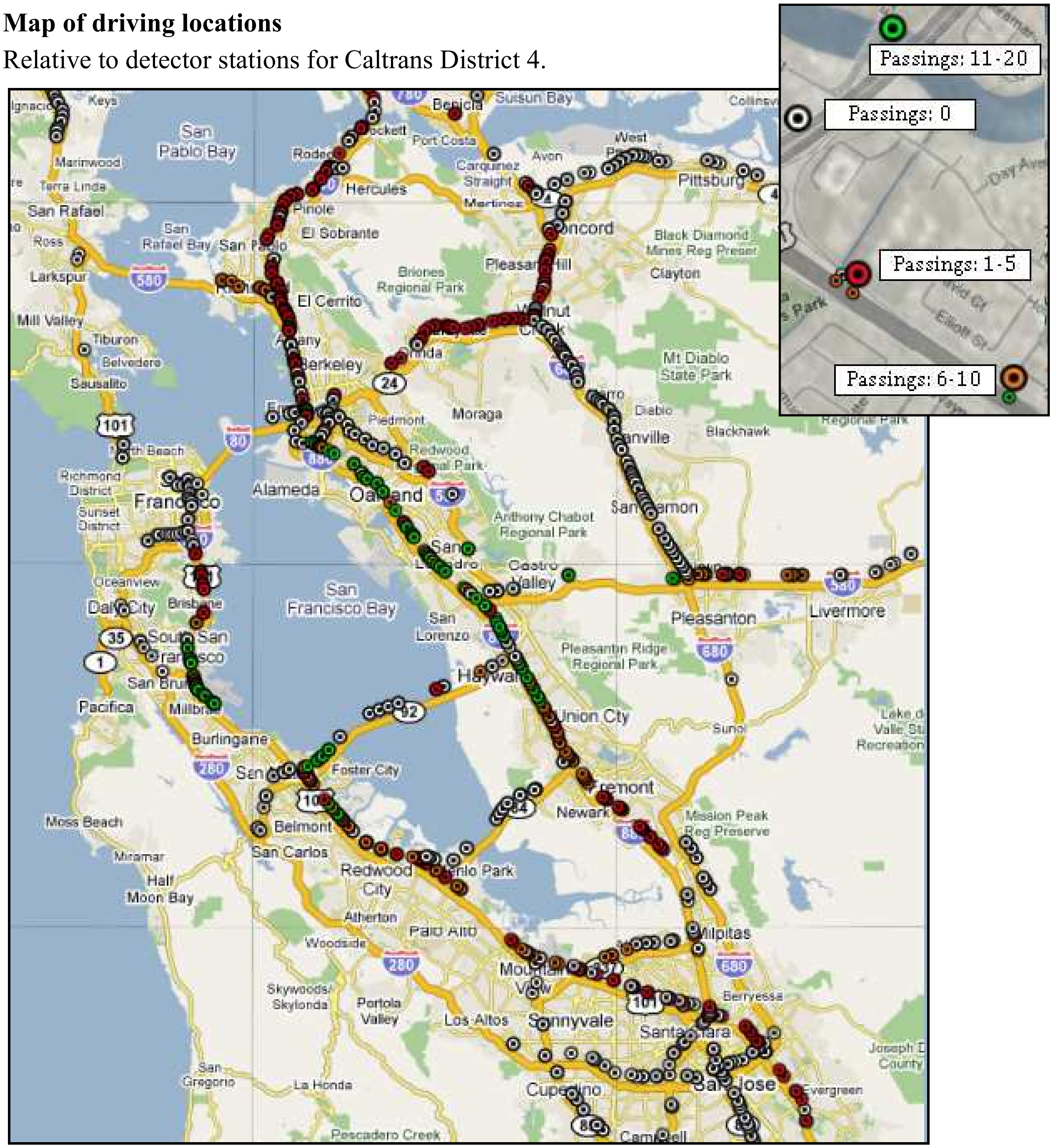
Chapter 9 Appendix

Map of driving locations

Relative to detector stations for Caltrans District 4.



The dots represent the number of crossings of each station by drivers 1 through 9.

Chapter 10: Concluding Remarks and Next Steps

This report has described the initial phases of work conducted under the project, "Developing and Evaluating Selected Mobility Applications for VII" in the task areas for which Caltrans has provided cost share funding through PATH Task Order 6224. Although much has been accomplished in these tasks, as reported here, these are still works in progress and more work remains to be done under the FHWA Exploratory Advanced Research Program and a successor Caltrans-funded cost share project.

The main accomplishments reported here include:

- refinement of the concept of combining variable speed limits with coordinated ramp metering to mitigate or eliminate traffic breakdowns on freeways;

- development of an improved and simplified second-order macroscopic traffic model that has high enough fidelity and computational efficiency to be used inside a mathematical optimization framework to select preferred reference speeds;

- identification of quantitative measures of the probability of traffic breakdown as a function of traffic speed and density, based on empirical data from specific highway sections;

- development of a nonlinear optimization method for choosing the preferred reference speed for a highway section to minimize traffic breakdowns;

- initial results demonstrating in simulation the potential for eliminating a traffic breakdown by use of the proposed method;

- development of a microscopic simulation of a freeway corridor that can be used to evaluate the effectiveness of alternative control strategies before they are proposed for field testing;

- implementation of the cooperative adaptive cruise control (CACC) system on top of the existing adaptive cruise control (ACC) system so that naïve drivers from the general public can drive the systems on their daily commute trips;

- design of the human factors experiment to identify how drivers use both adaptive cruise control systems and to quantify their propensity to choose shorter gaps if those are enabled by the CACC system;

- collection and analysis of data from the first 12 naïve drivers of the ACC and CACC systems;

- integration of the data collected on the ACC and CACC vehicles with infrastructure-based traffic detection system data in the PeMS database to identify the relationships between traffic conditions and ACC usage.

These set the stage for the next phases of work on the project, which will include:

- testing the optimization approach to choosing variable speed limits under a range of conditions and quantifying its effectiveness in improving traffic conditions;

- developing a real-time implementation of the variable speed limit optimization along the Berkeley Highway Laboratory (BHL) section of I-80 and communicating these real-time variable speed limits to the CACC test vehicle;

- testing the CACC vehicle with the real-time variable speed limit used as the CACC set speed in the BHL test section, and using the BHL video tracking system to characterize the interactions between this vehicle and the surrounding vehicles that are not subject to this speed limit;

- designing a human factors experiment to test the user acceptability of a variable speed limit display inside the vehicle;

- conducting the human factors experiment on variable speed limit displays, identifying the reactions of naïve drivers to a speed limit that could be significantly slower than the prevailing speed on the section of highway they are driving;

- using microscopic simulation to estimate the effects that the variable speed limit system could have on mitigating traffic breakdowns;

- completing the analysis of the CACC human factors experimental data from the remaining test subjects, up to the total of 16;

- using microscopic simulation to estimate the effects that CACC could have on increasing highway lane capacity when drivers choose the gap settings that they chose in the human factors experiment.