EOG Signals in Drowsiness Research

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Abstract

Blink waveform in electrooculogram (EOG) data was used to develop and adjust the method of drowsiness detection in drivers. The origins of some other waveforms in EOG signal were not very clearly understood. The purpose of this thesis work is to study the EOG signal and give explanation of different kind of waveforms in EOG signal, and give suggestions to improve the blink detection algorithm.

The road driving test video records and synchronized EOG signal were used to build an EOG library. By comparing the video record of the driver's face and the EOG data, the origin of the unknown waveforms were discovered and related with the driver's behavior. Literature descriptions were given to explain the EOG signal.

The EOG library is the main result of this project. It organized by different types of EOG signal. Description and explanation were given for each type of waveform, as well as some examples. The knowledge gained from the previous research review and the EOG library gives some improvement suggestions for the blink detection algorithm. These suggestions still need to be verified in practical way.

Keyword:
EOG, Drowsiness, Blink, Morphology, Driver, VTI

Acknowledgment

This thesis project is the final part of the master program in Biomedical Engineering at the University of Linköping. The project was carried out at the Swedish National Road and Transport Research Institute (VTI) and the purpose was to analyze electrooculogram (EOG) signal in order to improve the blink detection algorithm in the future research.

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Linköping, June 2011

Chongshi Yue

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1 Introduction

This thesis project investigates the blink behavior and other eye movements related with automobile driver during long time driving. The main aim is to map certain events in a recorded electro-oculogram (EOG) to actual blink behavior as measured via video of the drivers face. Based on the obtained knowledge, it will be possible to improve the detection method for driver's eyelid blink and to develop more robust measures of the driver's drowsiness state.

1.1 Background

The alertness state between alert wakefulness and sleep with reduced awareness and impaired psychomotor performance is called drowsiness (Johns, 2007). Drowsy driving is a major cause of motor vehicle accidents. The National Transportation and Safety Board (US) has pointed out that sleepy driving is one of the most important contributing factors for road crashes (NTSB, 1999). The influence of drowsiness to the driving safety can be as much as alcohol does. An investigation made by National Sleep Foundation in 2005 shows that 60% of the American adult drivers (nearly 168 million people) have experience of driven a vehicle while feeling drowsy in the past year (National Sleep Foundation, 2011). During the period 1989 - 1993, about 56,000 crashes annually happened on U.S. highways related with sleepiness driving according to the police accident reports, and drowsiness is also confirmed as a factor, which triggers an annual average of 1357 fatal crashes, resulting in 1544 fatalities from 1989 to 1993 (Robert D. Peters, 1999). A new investigation shows in Sweden 38 % of all fatal crashes, 33 % of all crashes with slight and severe injuries on motorway are sleepiness related.

In order to measure a person's alertness status, several techniques can be used. Electroencephalography (EEG) is one of the methods used to record the electrical potential along the scalp produced by the neurons within the brain. Some waveforms in the EEG signal are highly correlated with the participant's sleepiness level. This method is usually used in clinical environment to study the procedure when participants fall asleep. In the traffic safety research area, interests are in the physiological changes of the involuntary sleep, when the automobile driver tries to resist falling asleep. We don't have sufficient knowledge how to interpret EEG signals during this procedure.

Another option is to monitor the eyelid motion and measure drowsiness with a magnetic search coil. In this method, a small lightweight wire coil is affixed directly to the upper eyelid of the test subject. The subject's head is positioned at a center of a magnetic field, and the search coil produce an electrical signal when moving across the magnetic field with the eyelid. This technique is the gold standard for measuring variables of blinks, but it cannot be used for routine driving test, because it requires immobility of the subject's head and calibrations for each setup (Evinger, 1991).

Therefore, if an onboard system, which is able to monitor the driver's fatigue status and produce a warning when symptom of low awareness is detected it could make a big contribution to the transportation safety. Some systems based on recording head movements;

tracing steering wheel or monitoring other variables have already been developed for this purpose. At the Swedish National Road and Transport Research Institute (VTI), a project based on tracking the driver's eye movement with video camera has been developed. In order to have enough knowledge about blinks and the driver's alertness status, we applied a technology called Electro-oculogram (EOG) to measure and analyze driver's eye movements and blink during road driving tests. The previous period of this project has collected some data from on road driving test for many voluntary participants in both daytime (alert) and night (sleepy) driving.

The data amount collected from previous work is huge, however, the knowledge of EOG morphology is still insufficient and many EOG signal events remain unknown. When developing an algorithm to measure blink behavior, those unknown waveform can lead to inaccuracy in the result since some real blinks are missed and some non-blinks are detected.as normal blinks. These problems are what need to be solved in this project by creating a dictionary to translate between EOG events and actual eye movement or eye blink behavior.

1.2 Problem Definition

In this master thesis project, we try to give a detailed interpretation of the EOG signal appearance, find out the relationship between some specific EOG waveforms and the driver's eye movement and obtain more knowledge on how the EOG signal can be used to detect drowsiness. The method used to study the EOG signal is to compare the raw EOG data with the synchronized driving test video records, resulting in an EOG library which provides detailed descriptions for different kinds of eyelid movements. It includes the definition of each kind of eyelid movement, the EOG signal description and the example of how it appears in a driving test video.

1.3 Outline of The Thesis

Chapter 1 and chapter 2 are intending to discuss the background theory of this project, giving an overview about the fundamental knowledge needed for the project work. Chapter 4 covers the main results of this project. In the EOG signal library, we describe how the driver's motion affect EOG signal and explain some classical signals we found in EOG data related with blink studies. Chapter 5 will discuss how the knowledge gained from the EOG library can be used to improve algorithms designed to detect blinks in the EOG signal. The last chapter gives the discussion and conclusion for the whole project.

2 Background Knowledge about Blinks and EOG

When upper and lower eyelids temporarily touch and the eye is hidden, an eye blink occurs (Andreassi, 2000). The eyelid provides suction across the eye from the tear duct to the entire eyeball to keep it from drying out. Blink helps to keep the eyeball surface moistly by spreading tears and removing irritants from the surface of the cornea and conjunctiva. The upper eyelid fall down during a blink and the lower part almost keeps motionless. Some factors can affect the blink speed such as fatigue, eye injury, medication, and disease.

2.1 Physiology and Anatomy of Blinks

There are multiple muscles that control the reflexes of blinking. The main muscles (see figure 2.1), in the upper eyelid, that controls the opening and closing are the orbicularis oculi and levator palpebrae superioris (LPS) muscle and minor contribution from Muller's muscle. Orbicularis muscle extending from the regions of the forehead and face and surrounding the orbit into the lids (Iwasaki & Kellinghaus, 2005). Three forces dominate upper eyelid movements: two skeletal muscles, a smooth muscle and a passive force produced by mechanical arrangement of the eyelid. The arrangement of the ligaments and the insertion points of skeletal muscles produce a constant passive downward force on the upper lid (Evinger, 1991). The orbicularis oculi closes the eye, while the relaxation and contraction of the levator palpebrae muscle opens the eye. The Müller's muscle, or the superior tarsal muscle, in the upper eyelid and the inferior palpebral muscle in the lower eyelid are responsible for widening the eyes. The inferior palpebral muscle is coordinated with the inferior rectus to pull down the lower lid when one looks down (Iwasaki & Kellinghaus, 2005).

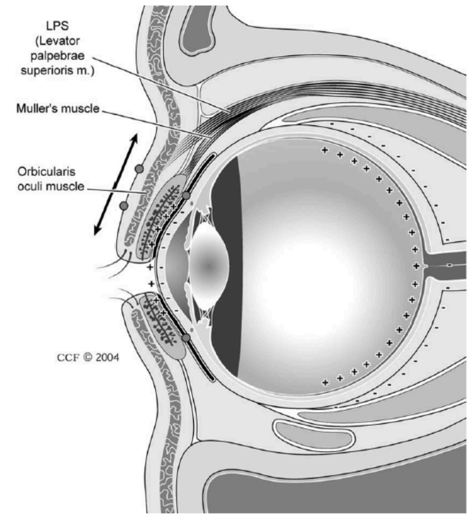


Figure 2.1: Anatomy of the main eyelid control eyelid movements and blink (Iwasaki & Kellinghaus, 2005).

2.2 Eye movements

Eye movements are controlled by the cortical and subcortical system in conjunction with cranial nerves and sets of eye muscles as mentioned above. They can be distinguished into three common types of eye movements (Andreassi, 2000):

1. Saccadic: This refers to the rapid ballistic jump movements of the eyes from one fixation point to another. A fixation pause lasts for about 0.25 to 1 second, and the saccade lasts for about 0.02 to 0.1 second. Because of the fast eye movement during saccades, there is not enough time for the nervous system to process visual information. Saccadic gaze shifts are often accompanied by blinks. (Rottach, 1998)

2a. Smooth Pursuit: Eyes fixates at a moving object and follow it. The rate of eye movement can closely approximate that of the object.

2b.Smooth Compensatory. This movement is to correct for body or head tilt to maintain visual field stable.

3. Nystagmoid: Oscillation of the eyes, occurs in response to an inertial rotation of body or visual field. It consists of slow horizontal sweeps and quick returns to the original eye position.

2.3 The Nature of Eye Blinks

The eye movements introduced above are the movements of the eyeball. The blink is more concerned about the movements of eyelid. There are three types of blinks: one voluntary and two involuntary. Voluntary blinks occur with a conscious decision to momentarily close the eyes. One type of involuntary blink is considered to be protective and is produced in response to some potentially harmful stimulus and is called as a blink reflex. A second type of involuntary blink occurs spontaneously about 15,000 times per day and keeps the cornea healthy by enabling a layer of moisture to form continuously (Andreassi, 2000). The last kind of blink is our main interest in the study of drowsiness. Its variables like frequency and duration are highly related to the alertness states of the participants (Johns, 2005).

2.3.1 Blink and Cognitive Processes

Activities that require thought or attention, leads to a decrease in blink frequency (Andreassi, 2000). When confronted with a visually demanding task, blink rate decrease significantly (Fogarty & Stern, 1989). During reading there is an inhibition of blinking, which becomes more pronounced related to the reader's interest in the material. A burst of blinks then occurs during the time when the reader turns the page (Andreassi, 2000). Oculomotor control system is very sensitive to fatigue, boredom, and lapses in attention. Long closure duration, the time the eyes remain closed during blinking, is related to reduced alertness. Lower blink rate and shorter blink duration were found in a visual task than an auditory one. Studies also found that blinks are delayed until decision about external stimuli has been made and response to those stimuli completed. As mentioned in previous section blinking was also found to be time linked to saccadic eye movements in a way that would minimize the disruption of visual information processing. The lower blink rate reflects the greater attention demanded of participants performing the more difficult task. (Andreassi, 2000)

An increase in blink frequency increase generally reflects negative mood states, such as nervousness, stress, and fatigue. Negative emotional states that accompany poor performance have been related to increases in blinking. More positive states are accompanied by decreased blink frequency.

2.3.2 Blink and Sleepiness

Much research has been done to study the relation between human blinks and the alertness states. Researchers suggest the separate durations of eyes closing, remaining closed and reopening, all tend to increase with drossiness (Johns, 2005). A blink parameter study with infrared reflectance method showed that the mean duration of eyelid closure and reopening increased significantly after sleep deprivation. However, the correlations between these different components of blinks are quite low (Johns, 2005). This result demonstrates there are different reflex processes that control separate components in the eyelid movement. They are somewhat independent. As discussed in section 2.1, different muscles dominate the down-phase and up-phase of eyelid movements. Therefore, when study the drossiness of car drivers by processing the EOG signal, it is important not only rely on one variable alone. Synthesizing different variables of blinks can give a more reliable and accurate result.

2.4 Recording of Eye Blinks

Eye movement measurement techniques general fall into three main categories: a search coil which employ a tiny wire and a magnetic field to measure; electro-oculography (EOG), which uses surface electrodes attached to the participants skin to measure corneo-retinal electrical potential; optical techniques that rely on optic sensors (e.g. video camera) to detect the eye movement.

2.4.1 EOG Signal

The front of the eye (cornea) has a bioelectrical potential that is positive with respect to the back of the eye (retina) and varying from 0.4 to 1.0mV (Malmivuo & Plonsey, 1995). The potential is approximately aligned with the optical axis of the eye. Using surface skin electrodes placed around the eye, the potential can be registered. This technique is known as electrooculogram (EOG).

Measurement of EOG

EOG signal can be measured in two channels: vertical and horizontal channel. It is obtained by placing electrodes vertically and horizontally around the eyes. Horizontal channel can record the eye movements in horizontal direction and vertical channel can record the vertical movements of eyeball, but more importantly, vertical channel also records the eyelid movements (e.g. blinks), which are our main interests in this project. Figure 2.2 shows how electrodes are placed on the participant's skin.

It can be seen in figure 2.3 that, if the electrical dipole orientation constituted by corneo-retinal potential is perpendicular to the connection line of two EOG electrodes, the differential voltage between the electrodes would be zero and it will increase with the rotation of the eye. The EOG may vary from 0.05 to 3.5 mV for eye movements up to 70 degrees. When the eyes are moving, the potentials at the electrodes vary proportionally to the sine of eye's rotation angle, the linearity becomes progressively worse for angles beyond 30 degree. When the muscles of the eyelids are moving, there will be a large change in the potentials around the eye. In EOG the normal blink is an upward signal changing, and it is almost immediately followed by a downward signal change known as it's reopening after reaching the peak.

The description above only considers the ideal situation; in practice more realistic factors need to be considered, such as the dc drift, skin conductance variation and corneo-retinal potential changes with light adaptation (Borah, 2006). The noise in EOG recordings arises from different sources like facial muscles, body, head movement and other activities like speaking (Malmivuo & Plonsey, 1995). When it comes to blink detection, the eyelid that is not related with blink can impair the result of blink detection. These eyelid movements are related with face muscle movements or head move, but in EOG signal it looks similar to normal blinks.

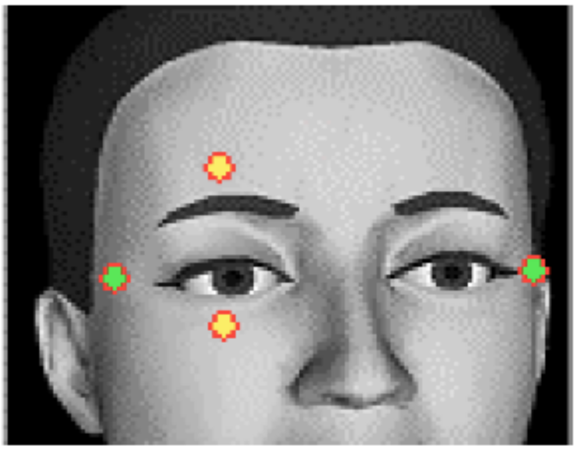


Figure 2.2: The electrodes placement, vertical channel (yellow) & horizontal channel (green) (Kircher, 2001).

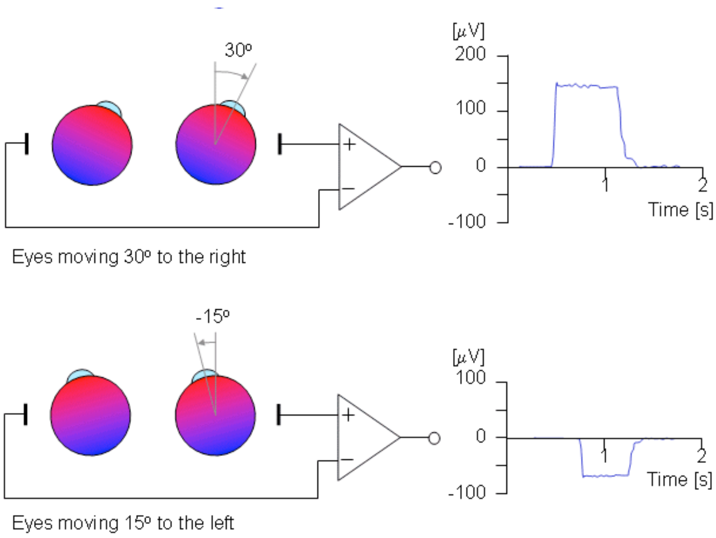


Figure 2.3: An illustration of EOG signal generated by horizontal movement of eyes (Malmivuo & Plonsey, 2000).

2.4.2 Blink Signal and Variables

A normal spontaneous blink in EOG signal usually has an amplitude range from 100 to 400 µV and duration for about 200 to 400 ms. Figure 2.4 shows a normal blink in the EOG signal. The blink waveform is inside the red box in the figure. It starts at the time point 00:48:16 and lasts about 300 ms. The up-phase of the blink wave corresponds the closure of the eyelid, when the eyelid move downwards, the amplitude of the EOG signal increase, the slope of the increasing phase in EOG signal represents the velocity of the eyelid movement. After the signal reaches the peak amplitude at 300 µV, it begins to drop very sharply. This stage of EOG signal corresponds to the upwards movement of the eyelid, the reopening of the eye. As can be seen, at the end of the reopening stage, the eyelid velocity decreases before the blink ends. Parameters used to describe the blink wave in EOG signal include blink frequency [blinks/minute], peak amplitude [µV] and the duration [ms].

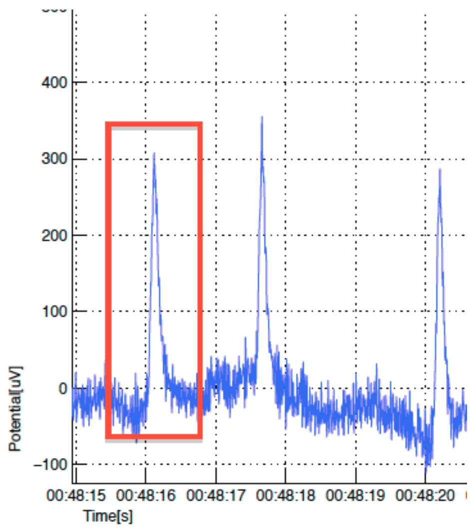


Figure 2.4: A normal blink wave in EOG signal, x-axis: time, y-axis: amplitude (µV).

From research results, by using search coil and orbicularis oculimuscles(OO-EMG) measure of the eyelid movement, researchers found the spontaneous blinks duration to be 334±67 ms, the down-phase lasted 92±17 ms, and up-phase 242±55ms. Voluntary blinks showed a short total duration of 275±37 ms. Electrically stimulated blink reflex had a total duration of 205±18 ms, which is the shortest in three kinds of blinks. In general, down-phase of a blink is shorter than up-phase. The blink duration and amplitude is measured as figure 2.5 (VanderWerf, 2003)

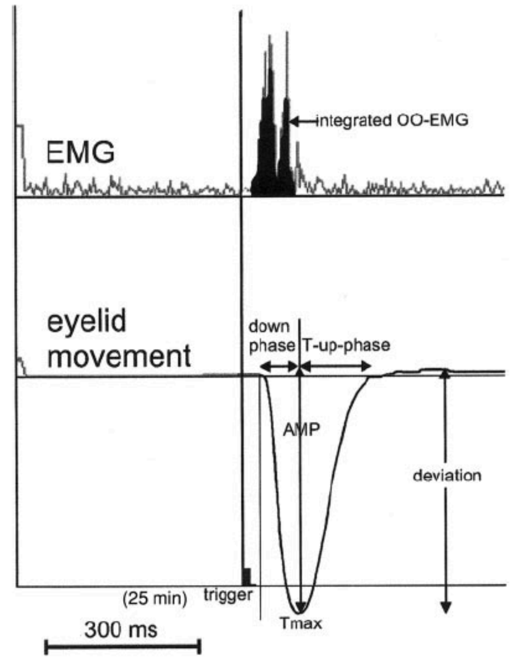
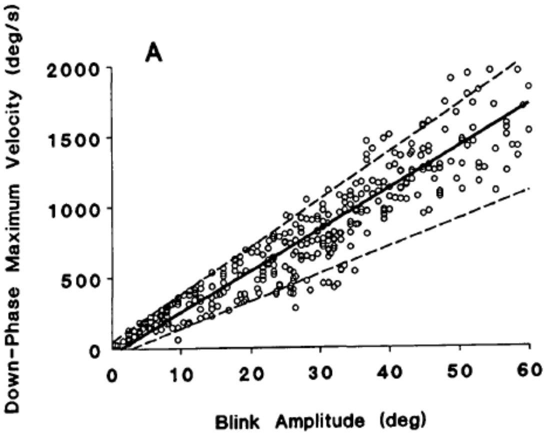


Figure.2.5: Schematic representation of kinematics of an upper eyelid movement (recorded by search coil) and the simultaneously recorded OO-EMG of a normal reflex blink (VanderWerf, 2003). T-up-phase, the up-phase time duration is defined as the termination of the blink minus the time the maximal deviation.

In another study with different eyelid movements (voluntary, spontaneous and reflex blink), also done by using the search coil and OO-EMG signal, researchers found eyelid downward movement to be faster than upward. The maximum velocity achieved during lid closing and opening is a linear function of the blink size (Figure 2.6). This relationship applies well to group data as well as single subjects (Figure 2.7). This linear relationship of blink amplitude and velocity (Table 1) has an important characteristic that there is a low inter-subject variability across wide ranges of blink conditions. For equal size, down-phase maximum velocity is slightly more than twice as fast as the maximum velocity of up-phase (Evinger, 1991).



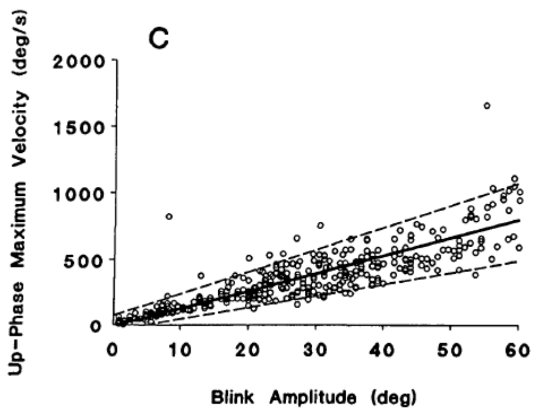


Figure 2.6: Maximum Down-phase (A), Up-phase(C) velocity of blinks plotted as a function of blink amplitude (Evinger, 1991).

Table 1. Best fitting regression lines determined for lid movement kinematics from all subjects*

	Maximum Velocity	
	Down-Phase	*Up-Phase*
Blinks	$Y = 29.2X - 35.9$	$Y = 13.5X - 5.87$
Saccades	$Y = 45.31X^{0.599}$	$Y = 13.3X + 14.82$
	Duration	
Blinks	$Y = 36.3 + 1.4X - 0.016X^2$	$Y = 87.9 + 4.3X - 0.047X^2$
Saccades	$Y = 33.2 + 5.9X - 0.069X^2$	$Y = 98.9 + 3.6X - 0.042X^2$

* X represents the amplitude of lid movement and Y symbolizes the expected maximum velocity of duration.

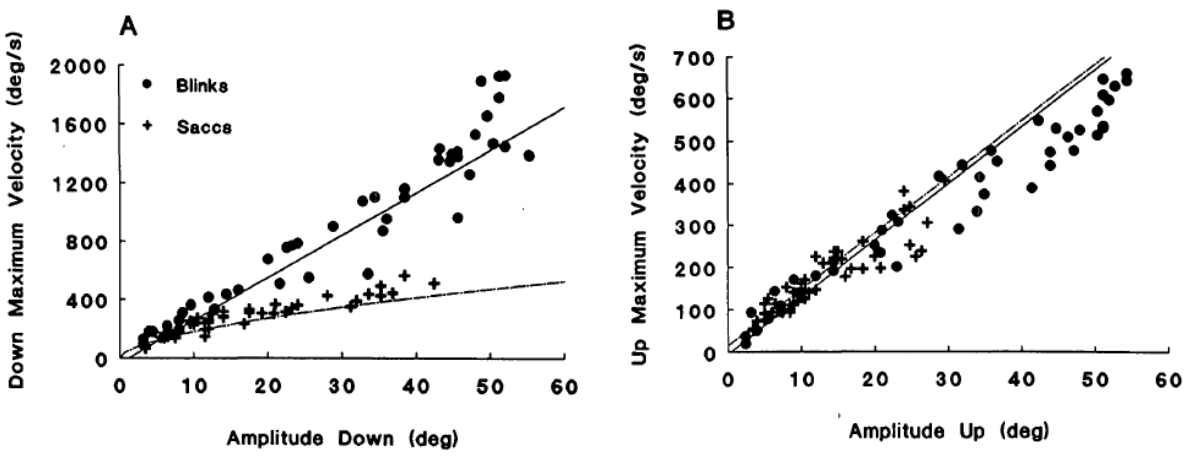


Figure 2.7: Single subject down-phase (A), up-phase (B) maximum lid velocity-amplitude relation +(lid saccades), ·(blink) (Evinger, 1991).

The relation between amplitude and duration is not linear (Figure 2.8). Since the maximum velocity of down-phase is larger than the up-phase, the time request to complete an equal amplitude down-phase blink is less than up-phase blink. We also found from figure 2.8 that blink duration changes a little with a large increase in blink amplitude. Reflex blinks have maximum down-phase velocity, voluntary blinks velocities are in the middle and spontaneous blinks are the slowest. Up-phase of three kinds of blinks achieves similar maximum velocities but spontaneous blinks have longer up-phase duration. (Evinger, 1991)

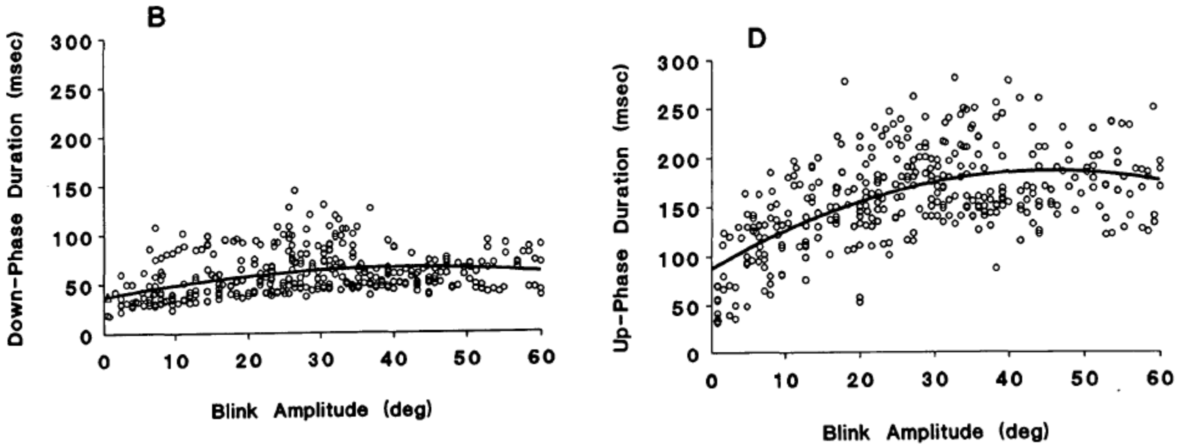


Figure 2.8: Blink amplitude and down-phase (B), up-phase (D) duration relationship (Evinger, 1991).

2.5 Summary

From the above review and synthesize of literature, blink duration and frequency are appropriate indicators to detect drowsiness, but if we want more reliable result, more knowledge about EOG morphology should be acquired.

The duration and amplitude of blinks in EOG are important variables in driver's alertness research. The raw data of EOG signal collected during driving test do not only include the blink signal but also contains noises of no interest. These noises including the electrical interrupt from muscles near the participant's eyes, the movements of the participant's head and some other behaviors of the eye except for blink. If we analyze the EOG signal without exclude these noise first, the result becomes unreliable. Therefore the study of the EOG morphology can provide a simplified signal and improving the algorithm of blink detection.

3 Material and Methods

The dat a material used in this thesis project was from a field test where the participants drove on a highway. Collected data, relevant for this thesis, are video recordings of the driver's face and the EOG data. The data were collected during in autumn 2010. Eighteen participants (10 men and 8 women) conducted two driving sessions in an instrumented car (Volvo XC70). The participants were recruited from the Swedish register of vehicle owners. The first session was an alert/baseline session, while the second was conducted after midnight when the participants were sleepy.

3.1 Instrumented Car

The car used in the experiment was a Volvo XC70 with an automatic gearbox. The vehicle was equipped with 3 data loggers. One of the loggers was acquiring data from a CAN network, external sensors such as GPS, and 4 cameras. The second logger was recording data from 2 different eye-tracking systems, and the third logger was acquiring physiological data. The cameras were recording vehicle frontal and rear view, the driver face and driver's feet. In this thesis project, we only use video of the driver's face.

EOG and physiological data (EEG, EOG, EMG and ECG) were recorded by Vitaport 3 (Figure 3.1). (TEMEC Instrument B.V., The Netherlands)

Figure 3.1: A Vitaport 3 recorder

3.2 Data Collection

The test route selected was the motorway E4 from Linköping to exit 128 and back (Figure 3.2). The length of test route was approximately 2 x 79 km and it took about 90 min to drive.

The posted speed limit was 110 km/h during the whole route, except for a road section of 750 m approximately 25 min from the starting point (and also from the end point), where the posted speed limit was 90 km/h. The road from VTI to the starting point, the turning at exit 128 and the road from the end point back to VTI are not included in the test.

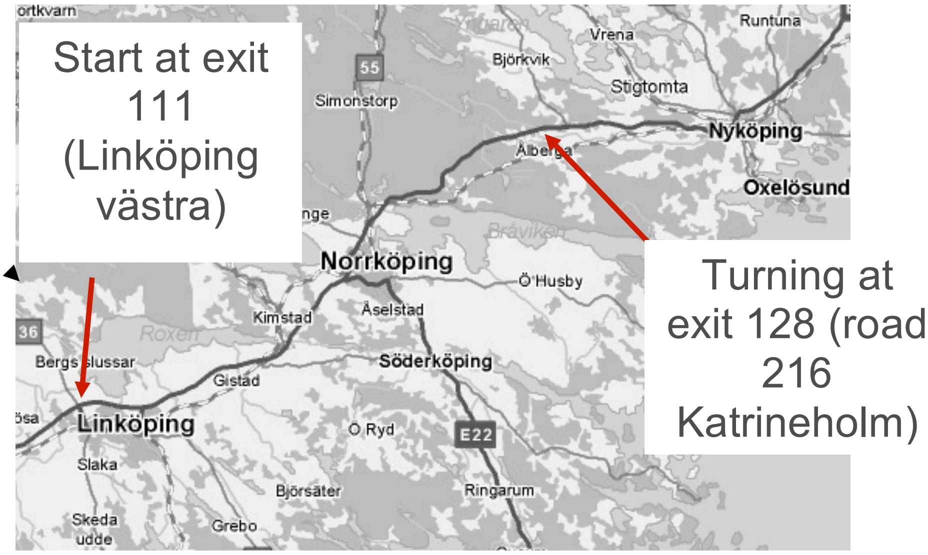


Figure 3.2: The test was conducted at road E4. The test route started at exit 111 in Linköping and the turning point was at exit 128.

Two participants participated each experimental day. The first subject arrived at 2 pm and the second at 4 pm. Each participant accomplished two driving sessions on each test occasion: the first was an alert condition and the second was a sleepy condition. The start and end times for the driving sessions are given in table 3.1. The start times for the alert conditions were chosen so that it would be daylight during the whole driving sessions.

Driving session	Start	End
Participants A alert	15:30	17:15
Participants B alert	17:45	19:30
Participants A sleepy	00:15	02:00
Participants B sleepy	02:45	04:30

Table 3.1: Start and end times for the driving sessions

Each driving session lasted for about 90 min. The participants were instructed to drive as they would do in "real life". During the test they were not allowed to speak, listen to the radio or do anything else that would counteract their sleepiness. A test leader was sitting in the front passenger seat monitoring the whole session and aborting the test if necessary.

3.3 Build of The EOG Library

EOG (two vertical and one horizontal channel) was sampled with a frequency of 512 Hz. Figure 3.3 shows the electrode positions.

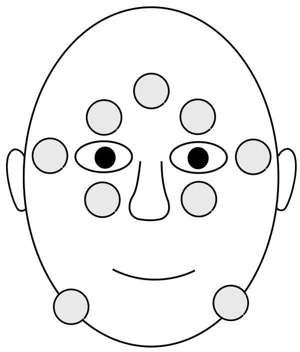


Figure 3.3: Electrode positions of EOG

Since the quality in some of the videos is not good enough make it is difficult to analyze the driver's eyelid move, why we only took 9 participants' data as our exam sample. The EOG data and driving video are synchronized in Matlab to have same time axis. EOG data was resampled to 256 Hz in order to decrease the time needed for computer plot the data. By review the EOG data and driving video, we constructed the EOG library.

3.3.1 Layout of the EOG Library

The EOG library is arranged in different classes of EOG signals found during the analysis. Each class of the EOG signal represents a general EOG morphology corresponding to a specific eyelid movement or face muscle movement. Some sections may contain smaller categories of EOG signals, which represent a more specific movement. Every class of EOG signal starts with a general explanation of what can be found from the video record, which is the physiological reason of this kind of EOG and followed by the morphology description of the EOG signal itself, finally some examples of the EOG signal plot is illustrated.

4 EOG Library

This chapter is the main result of this project. The preprocessing of EOG signal is descripted first, then the EOG library is presented.

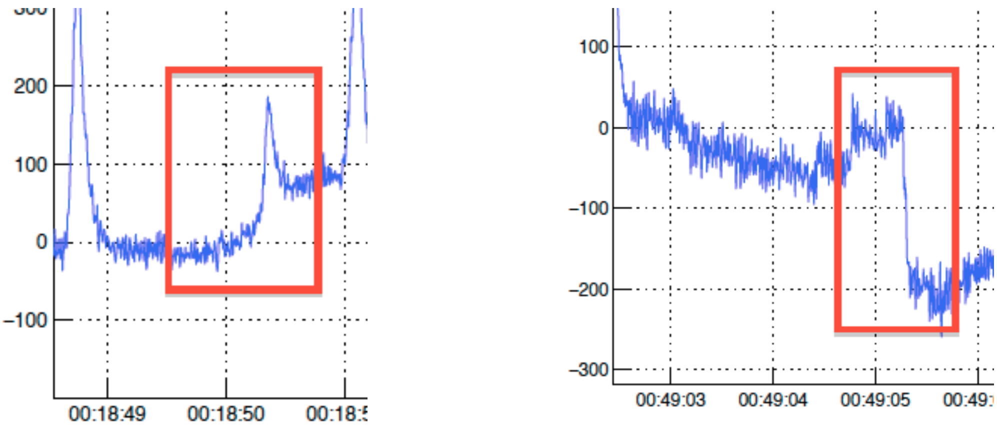
4.1 Synchronize, resample of data

The data used in this project to construct the library is the video recording of the driver's face and the EOG data. In the driving test records, a large number of waveforms are found unable to be recognized as the normal blink. The cause of many of these abnormal signals is unknown. In order to find out what kind of movements from the driver that leads up a particular EOG waveform, EOG data need to be compared with the driving test video. The video record starts from the preparation work in the VTI parking lot and ends when the car is driven back to VTI and the whole test session is over. The interesting content of the video record is start at when the car is on somewhere of E4 motorway and the test leader pushes a marker button which send a pulse signal to the physiological data logger. On the other hand, the EOG data starts right after the participants were attached to the measurement equipment. Although both the video record and the EOG data record there is a marker as an indicator of where the interest part of the test starts, but the time axis is different in these two data sets and it produce a lot of inconvenience for analyze and compare the video and the EOG signal. If any abnormal signal is found from the EOG signal, without synchronized time axis it will be almost impossible to find that specific time point from the video record.

In order to eliminate this inconvenience and make the comparison work more efficient, the EOG data was processed by cutting out the interesting segments and rearranging the time axis. As mentioned in previous chapter, the raw EOG data is sampled in 512Hz. In another project (Xie, 2010), experiments suggested that 256Hz is enough for reconstructing the EOG signal, so the EOG data in Matlab was resampled to save the time for plot and display the EOG signal. All pre-processing are done in Matlab and the codes are present in appendix.

4.2 Comparison of EOG signal and video

The main work for construct EOG library is the comparison of the EOG signal and driving test video. From the previous literature study, we had some basic pre-knowledge of how the EOG signal would appear correspond to some specific eye movements. The basic movement of the eyeball (rotate) in horizontal orientation gives the amplitude change in the horizontal channel of EOG data as well as in the vertical. In the vertical channel, if the participants rotate his or her eyeball upwards there will be an amplitude rise in the EOG signal, and when the participants look downwards, the signal will drop below baseline. Figure 4.1 shows the EOG signal change corresponding to the vertical rotation of the eyeball.
The eyelid movement also affects the EOG signal and it can only be distinguished in the vertical channel. The normal spontaneous blink emerges as a sharp rise and fall in EOG signal which has the time duration of 300 to 400 ms.



A **B**

Figure 4.1: EOG of looking up while blinking EOG, A (upward), B (downward), x-axis is time (hh:mm:ss), y-axis is amplitude in μV, the following figures in this chapter have the same axial units.

When we construct the EOG library, we start from the EOG signal. After pre-processing, the signal is displayed in Matlab with the same time axis as the video record. If we found signal we can confirm as normal blink, the signal is ignored, if some aberrant signal (large amplitude, long duration, deviant profile, etc.) appears in EOG, we check the video record to see what happen to the participant at the same time aberrant signal appears. We mainly focus on vertical channel since the blink can only be detected in this channel and the horizontal channel is checked when we want to verify the relationship between the strange signal in vertical channel and the participant behavior in the video record.

4.3 Normal blink

Normal spontaneous blinks are the blinks that can be used to measure the driver's drowsiness state. Most of the blinks found in road test records are spontaneous blinks. Normal blinks in EOG data usually appears as a sharp pulse with fast down-phase eyelid movement and relatively slower up-phase eyelid movement in vertical channel. The horizontal channel doesn't have any significant change. This kind of EOG signal pattern sometimes also appears in other eye movement signals, which means a blink is accompanied with the movement. Average duration of normal spontaneous blink is 300 to 400 milliseconds. Figure 4.2 shows two normal blinks EOG signals. The left figure shows a blink starts at time 00:48:16, the sharp increase in amplitude represents the downward movement of the eyelid, which is the closing of eyelid. When the amplitude reaches the peak value at 300 μV, it starts to decrease with a similar speed of the increase part; this stage is the eyelid reopening movement. When the amplitude drops to around 80 μV its changing ratio begin to slow down and the whole blink duration is around 400 ms. The right figure shows a similar profile of a normal blink with lower peak amplitude, which is about 200 μV.

Examples:

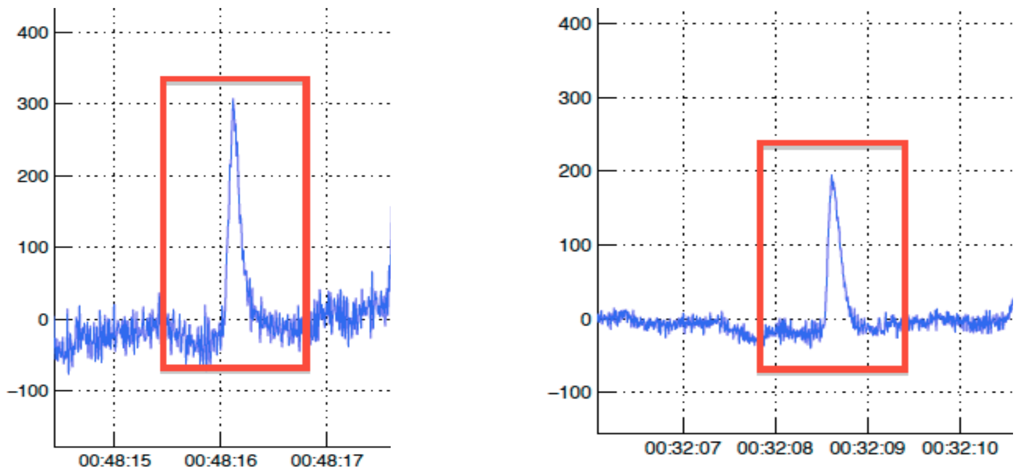


Figure 4.2: Normal blinks EOG signal

4.4 Blink with eye movements

The driver may change his or her viewpoint from one spot to another during the driving session. This is mainly due to the dashboard checking or rearview mirror checking. A blink can always be found after the driver move his or her viewpoint from dashboard, rearview mirror or some other places back to the front window and focusing on the road again. This kind of blink is accompanied with eye movement; therefore it's not relevant with the driver's alertness state so much.

4.4.1 Dashboard checking

When the drivers check the dashboard, they turn their viewpoint from the front window to the dashboard and keep it steady for some time before looking at front window again. The whole procedure lasts from less than 1 second to a few seconds. Sometimes the driver may repeat this action for few times in a short time.

From the EOG plot, the typical pattern of this kind of signal behaved as constant negative amplitude companied with a normal blink. Figure 4.3 and 4.4 show the typical dashboard checking EOG signal. From figure 4.3, it is clear the dashboard checking starts at 00:49:05 where the amplitude sharply decreased below zero, this is due to the driver turning his eye from the front window to the dashboard. Then the amplitude keep negative and steady for about one second, during this time, the driver's viewpoint is fixed on the dashboard. As mentioned above, there always a blink accompanied with an eye movement, the dashboard checking movement is end with a normal blink pattern after time 00:49:06. There may (Figure 4.5, 4.6) or may not (Figure 4.3, 4.4) be a blink before the driver focusing his/her eyes to the dashboard. Usually the time duration of dashboard checking is less than 1 second. In figure 4.6, the driver checked the dashboard three times, and every time the checking duration lasts more than 1 second.

Examples:

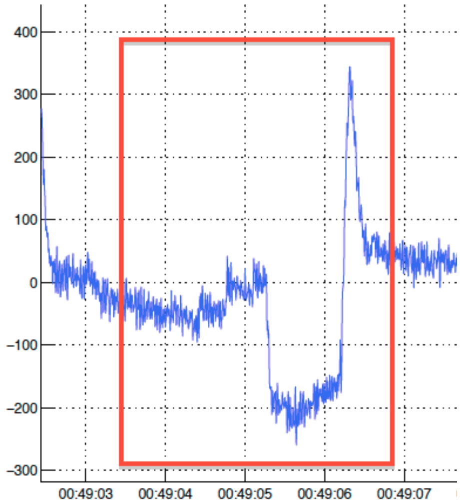


Figure 4.3: Dashboard checking EOG signal, without blink in advance. The action begins at time 00:49:05 and end with a normal blink signal.

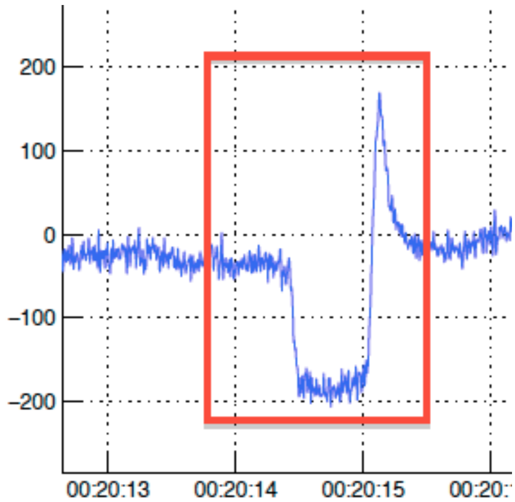


Figure 4.4 Dashboard checking EOG signal, action starts at 00:20:14.5, ends at 00:20:15.5

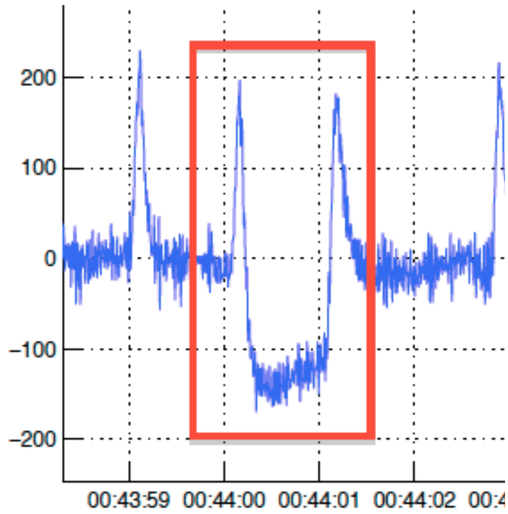


Figure 4.5: Dashboard checking EOG signal, blink appears before driver turn his view to the dashboard

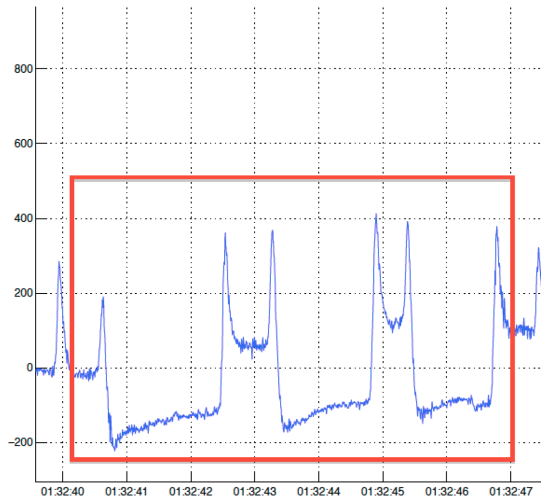


Figure 4.6: Checking dashboard several times with long duration

4.4.2 Rearview Mirror Checking

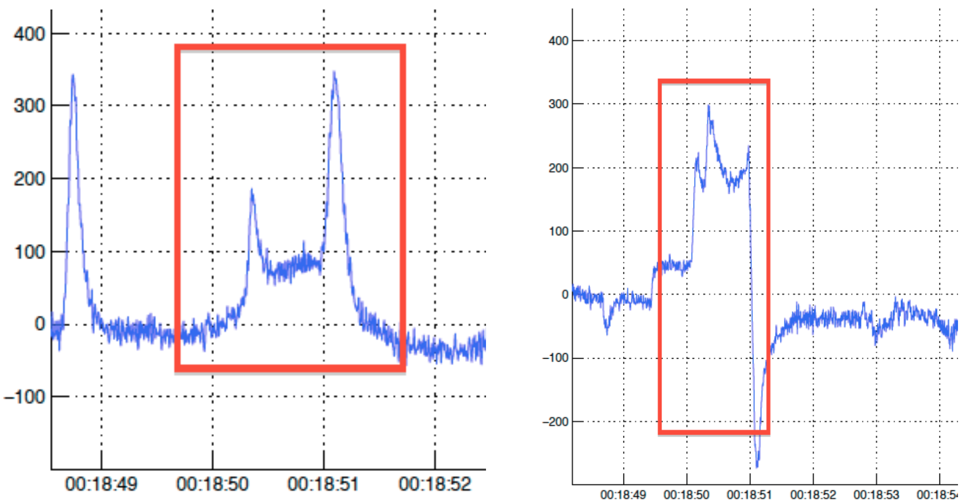
There are two kinds of rearview mirror checking movements: central mirror and side mirror. The driver will for example, perform this kind of action when they want to overtake other vehicles.

Central Rearview Mirror

In this kind of EOG signal, driver check the central rearview mirror by rise his view point and turn a little right, focusing on the central rearview mirror for some time, then turn back the view to the front window, blinks appears at the end of this movement. When the driver moves his/her viewpoint to the mirror, he/she can either rotate the eye upwards or raise the head a little.

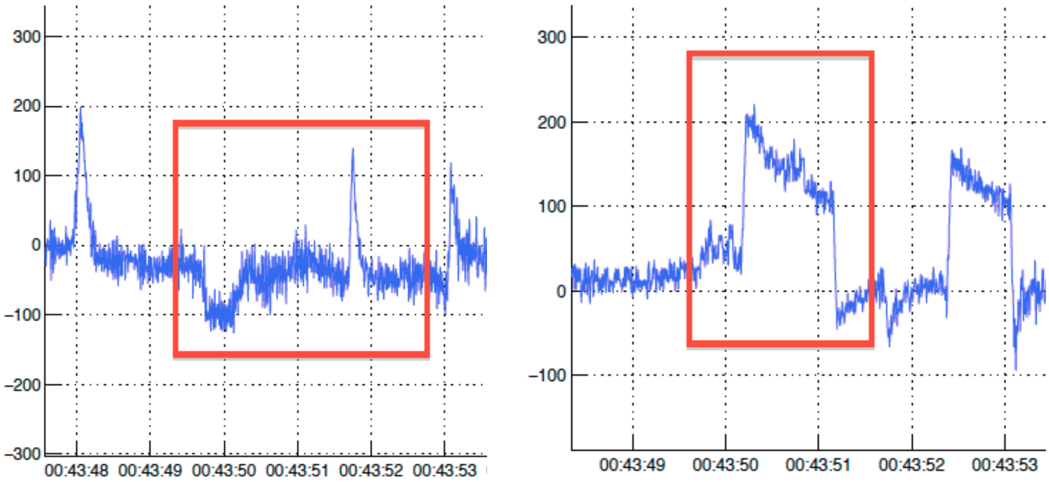
In figure 4.7, the driver turn his viewpoint to the central rearview mirror at time around 00:18:50, a normal blink pattern can be found at this time in the left plot. Meanwhile, the amplitude rises in the right plot, which is the horizontal channel of EOG signal. This positive amplitude in horizontal channel indicates the driver turning his eye to the right side. The positive amplitude in both vertical and horizontal channel in maintained for about half a second when the driver stare at the mirror. Finally, another blink pattern brings the signal back to the baseline. In figure 4.8, from the horizontal channel it's clear at time 00:43:50 the driver turn the viewpoint to the mirror, but no clearly normal blink pattern can be seen in the vertical channel at this time. The amplitude of vertical channel has no significant change in this case. This is due to the driver raise his head to look at the mirror instead of rotate his eyeball. At time 00:43:51 the amplitude decrease sharply in horizontal channel, it means the driver turn the viewpoint left side. At the same time we can found a blink pattern in the vertical channel, which confirmed that a blink always appear after the driver turn his/her viewpoint back to the front window. In figure 4.9 and 4.10, the EOG signal profile is similar to figure 4.7, but the first blink pattern has relatively lower amplitude. Figure 4.11 and 4.12 illustrate the case when there is an obvious blink both at the beginning and the end of this kind of eye movement. In figure 4.11, the driver stares at the mirror for more than one second, during this time the vertical channel amplitude drop a little and rise again before the final blink which ends the mirror checking action.

Examples:



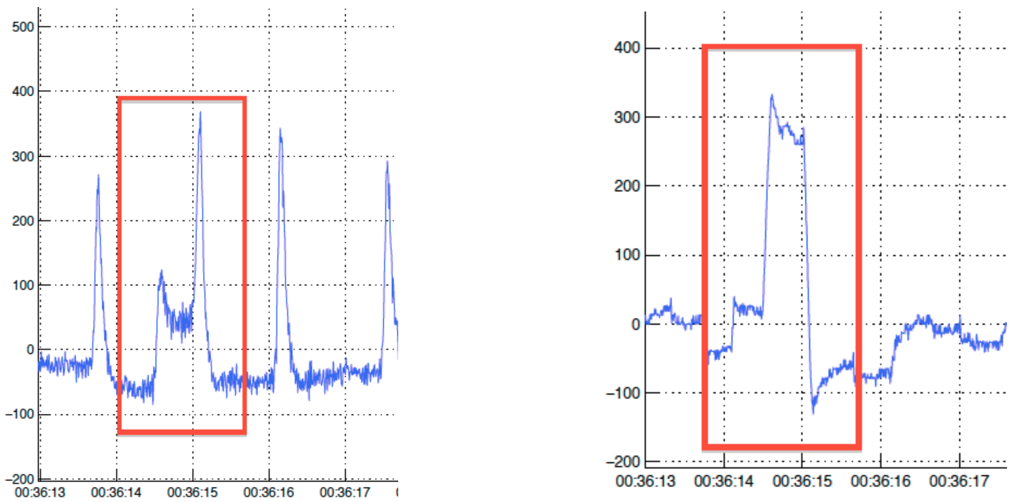
A　　B

Figure 4.7: Check rearview mirror, (A) vertical channel, (B) horizontal channel, the movement start at time 00:18:50.



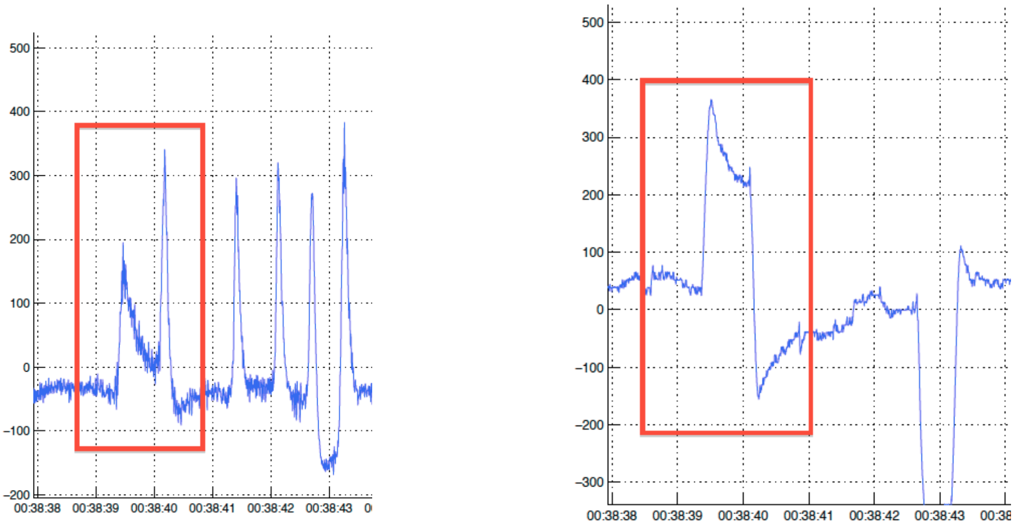
A B

Figure 4.8: Check rearview mirror, (A) vertical channel, (B) horizontal channel, there is no significant change in vertical channel during the movement.



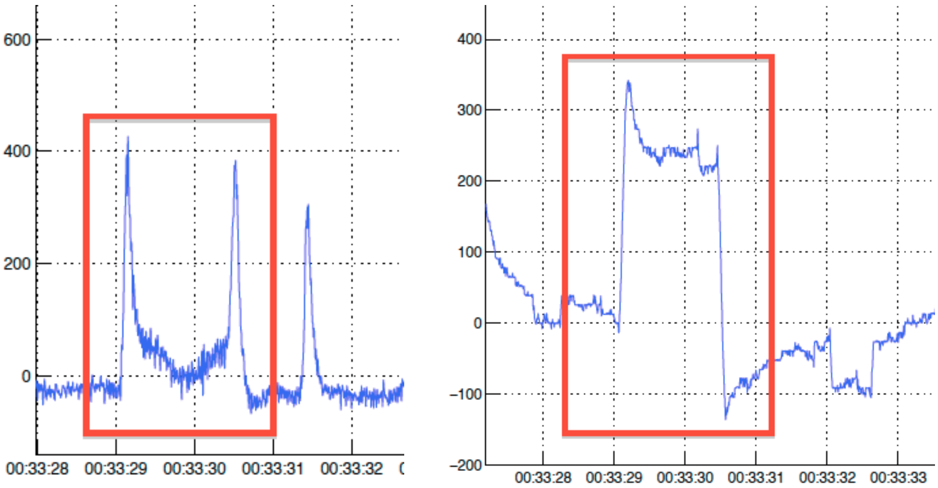
A B

Figure 4.9: Check rearview mirror, (A) vertical channel, (B) horizontal channel.



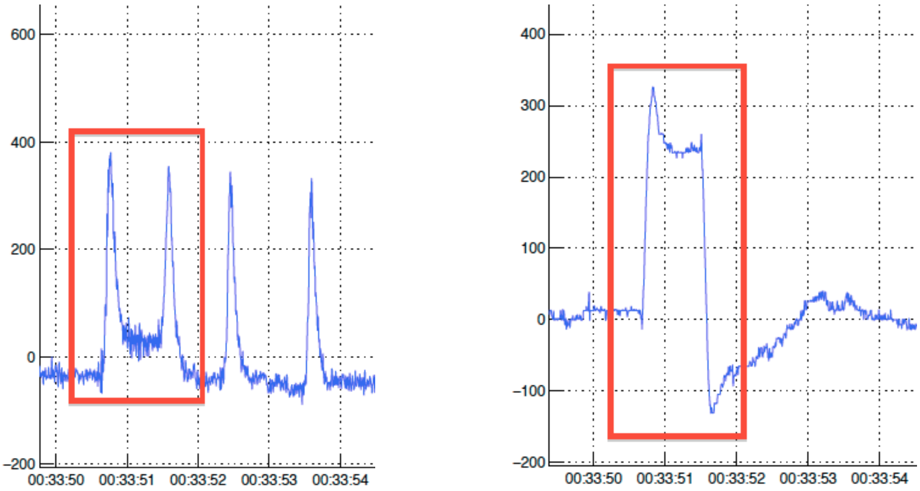
A B

Figure 4.10: Check rearview mirror, (A) vertical channel, (B) horizontal channel.



A B

Figure 4.11: Check rearview mirror, (A) vertical channel, (B) horizontal channel.



A **B**

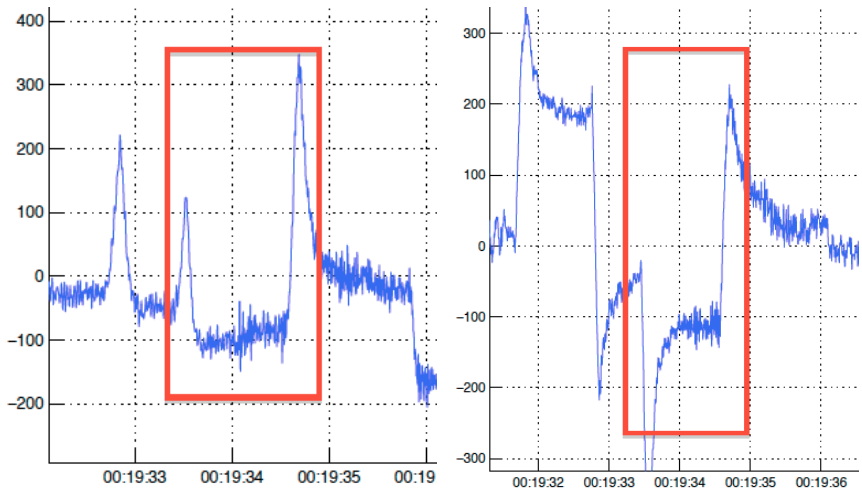
Figure 4.12: Check rearview mirror, (A) vertical channel, (B) horizontal channel.

Side Rearview Mirror

This kind of EOG signal is similar to the previous one (central rearview mirror checking). The driver turns his/her viewpoint to the side rearview mirror to check the traffic situation behind the vehicle and turn back to front window again.

Figure 4.13 shows the EOG signal when the driver checks the left side rearview mirror. In the vertical channel plot the movement starts at time 00:19:33, a normal blink pattern appears at the beginning followed with the amplitude decrease to a negative value. This part of the signal corresponds to the action that the driver turns his viewpoint from the front window to the left side rearview mirror. When the driver is focusing on the forward roadway the viewpoint is higher than the viewpoint of side rearview mirror, therefore the amplitude become negative after turning to the rearview mirror. When the driver turns his viewpoint back to the front window, there is also a blink and the amplitude returns to baseline. In the right plot, which is the horizontal channel signal, amplitude become negative during the whole movement, indicates the driver rotate his eye to the left side to check the mirror.

Examples:



A **B**

Figure 4.13: Check side rearview mirror, (A) vertical channel, (B) horizontal channel, the movement starts at time 00:19:33.

4.5 Muscular Movement Noise

EOG measure the electrical potential difference between the retina and the cornea by placing electrodes in vertical or horizontal positions on the skin surface. Therefore during the whole driver session, the electrodes not only record the useful signal from the eye movements, but it also interferes by the muscular electrical signal of the driver's face. Such muscular noises can be violent in the EOG data and result in huge amplitudes and low frequency noise. Blink during those noisy signals can be very difficult to be detected.

4.5.1 Yawning

During the night driving test session, yawning can be found continues appears in the video record. It is a signal that indicates the driver is becoming drowsy. The driver open the mouth widely with some face muscle stretched tight.

Yawn mainly affects the vertical channel of EOG signal. Figure 4.14 shows a yawn movement in vertical channel of EOG signal. By check the video record, the yawning is confirmed starts at time 01:12:10 and ends at 01:12:13. During this time six normal blink patterns can be found in the figure. The baseline of EOG signal changes violently. Figure 4.15, 4.16 give the extreme examples of the yawning effect on EOG signal. The signal baseline is distorted by the yawning action and the baseline amplitude change is far beyond the amplitude of the blinks, it even reaches the maximum measure range of the EOG instrument. In these situations, it will be very difficult to detect the blink. Figure 4.17 gives an example where the driver didn't open the mouth so wide during yawning and the baseline changes slightly in EOG signal. The yawning movement is always changing the vertical channel baseline amplitude from zero to negative value.

Examples:

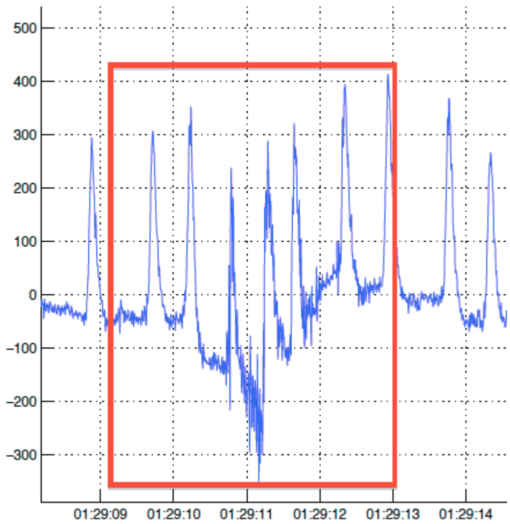


Figure 4.14: Yawning effect on EOG baseline, vertical channel.

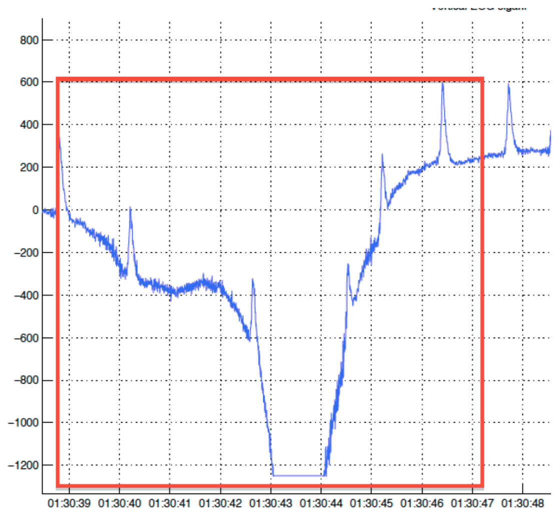


Figure 4.15: Yawning effect on EOG baseline, vertical channel.

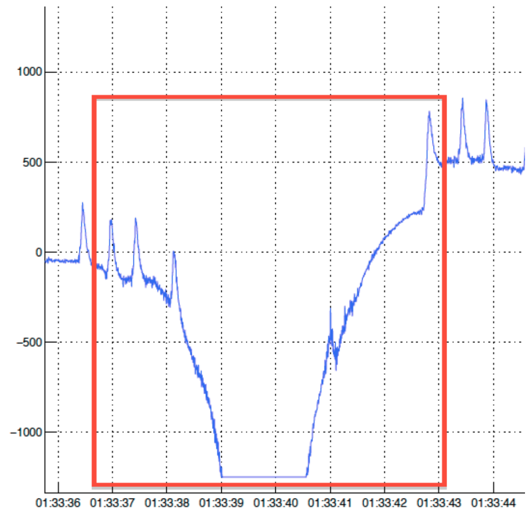


Figure 4.16: Yawning effect on EOG baseline, vertical channel.

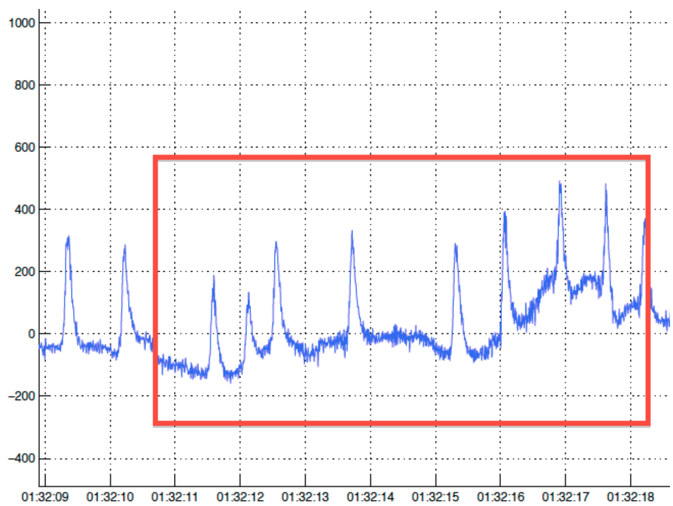


Figure 4.17: Yawning effect on EOG baseline, vertical channel.

4.5.2 Talking

During the driving test session, the participants sometimes need to talk with the researchers. The talking effect on the EOG signal is similar to the yawning effect. In the vertical channel, the signal baseline wander from the original level during the driver's talking action. It is also a low frequency wave and the amplitude is much smaller than yawning. In figure 4.18 the EOG signal baseline change from 0 to about -100 μV when the driver began to talk at time 01:17:40. In figure 4.19, the driver began to talk at time 00:22:04 and last 4 seconds. The EOG baseline changes from 0 to 100 μV. After the talking, the EOG signal baseline returns the original level again.

Examples:

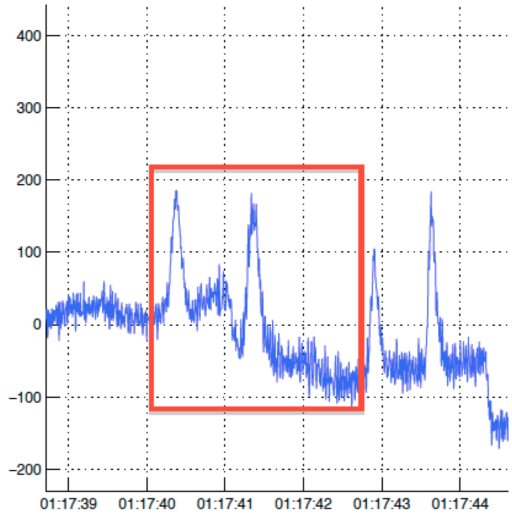


Figure 4.18 Talking effect on EOG signal, vertical channel

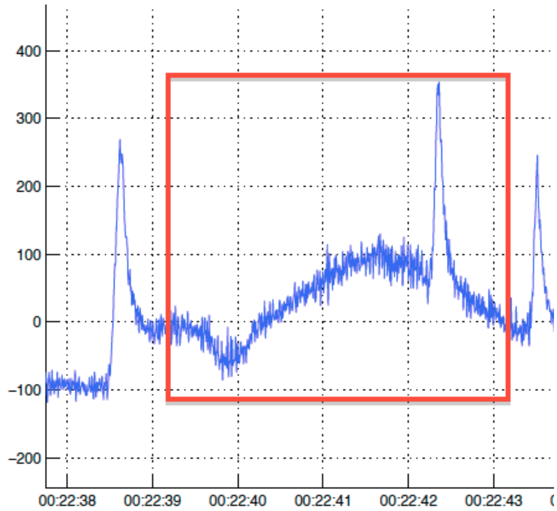


Figure 4.19 Talking effect on EOG signal, vertical channel

4.5.3 Head movement

During the driving test, the driver sometimes needs to check the traffic situation behind the vehicle where the rearview mirror cannot reach. At this time, the driver needs to turn his/her head to left or right in a comparatively large range. This kind of movement also produces noise in EOG signal.

In figure 4.20, an example of this kind of EOG is given. The driver turns her head to the right side to check the traffic behind the car. This action starts at time 01:01:38. In the vertical channel, a violent change in baseline amplitude can be found. Because the driver turns to look at right side, the horizontal channel signal's amplitude increases during this movement. This kind of EOG signal can be distinguished from yawning by checking the horizontal channel. The yawning mainly affect vertical channel, but when the driver turn his/her head to one side, the horizontal channel signal will definitely change.

Examples:

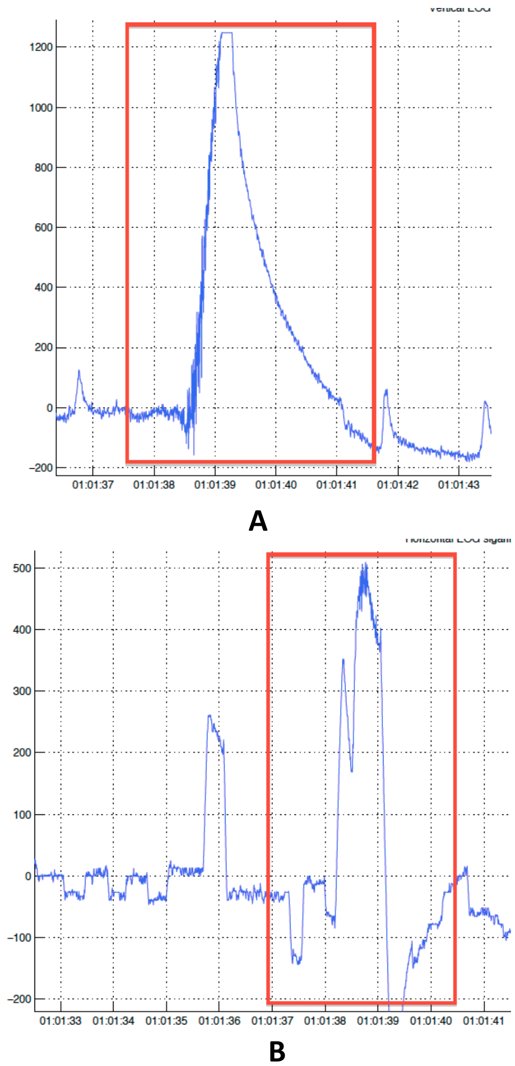


Figure 4.20: Head movement, (A) vertical channel, (B) horizontal channel

Lower of The Head

Sometimes the driver lower or raise his/her head a little when they stare at the front window. This action is probably due to the driver trying to relax their neck muscle after long time driving. When they lower or raise their head, their viewpoint still fixed at the front window and concentrate on what happen on the road.

Figure 4.21, 4.22, 4.23 shows the EOG signal behavior in vertical channel when the drivers lower their head. In figure 4.21, the driver begins to lower his head at time 01:01:48. The movement looks like slow nod from the video record. When he lowers his head, he's still focusing on the road in front of him and didn't rotate his eye in any direction. This specific action makes the upper side of his eyelid a little bit lower than normal and reflect a slowly increase in amplitude in the vertical channel (01:01:48-01:01:50). When the driver raises his head again, the upper side of the eyelid returns to its normal position as along with the EOG amplitude. If a blink occurs during this situation, it can be difficult to decide where exactly the blink starts if the head movement is too fast (Figure 4.23), which the rise of EOG signal merged with the up-phase of the blink signal.

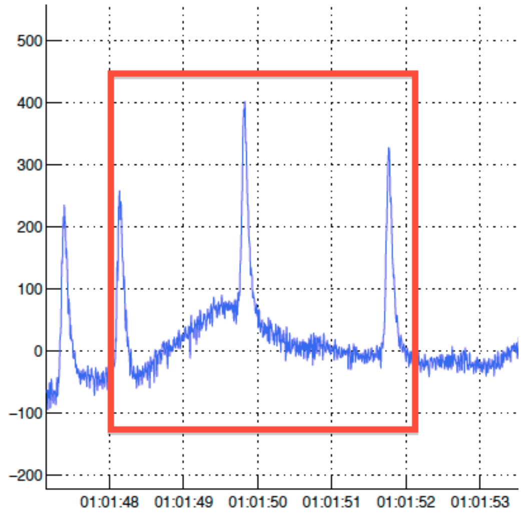


Figure 4.21: Lower head EOG, vertical channel.

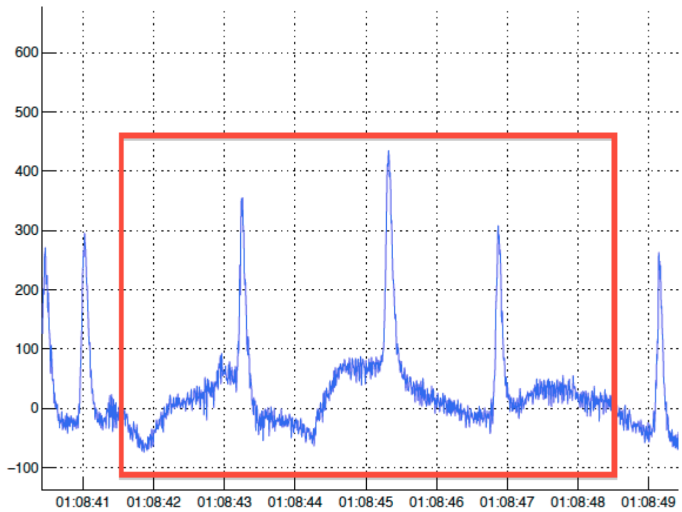


Figure 4.22: Lower head EOG, vertical channel.

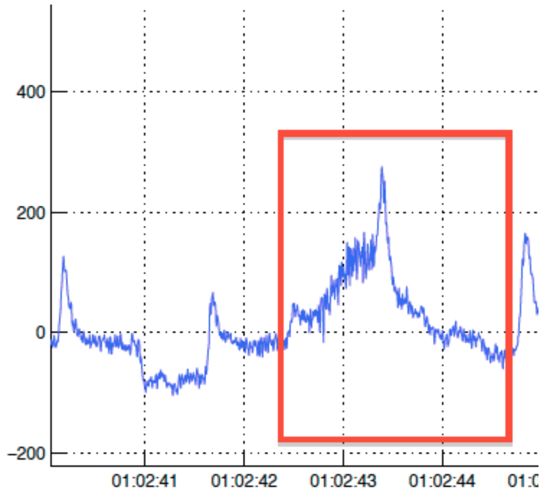


Figure 4.23: Lower head EOG, vertical channel.

4.6 Combinations of blinks and eye movements

The blink complex in the EOG may sometimes represent a combination of some eye movements or double blinks. The shapes of the complex are not regular and may result in error in detection of blinks.

4.6.1 Double blink

Double blinks indicate that the driver blink twice in a very short period of time.
In figure 4.24 and 4.26, the driver's eyelid move downwards half way then rise again, producing the first small amplitude wave in the red box. Immediately after this 'half blink', the driver completes a normal blink, which appears as a normal blink pattern in the red box. Figure 4.25 shows a double blink that looks like two normal blinks together. The vertical channel signal is sometimes similar to the signal when the driver is checking the central rearview mirror very fast. However, in the double blink case there is not significant change in the horizontal channel.
Examples:

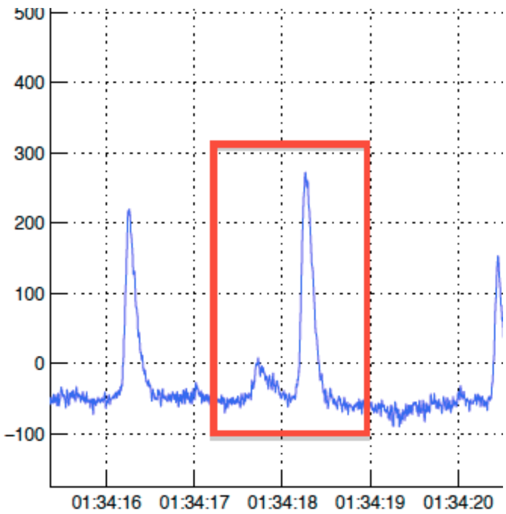


Figure 4.24: Double blink on EOG

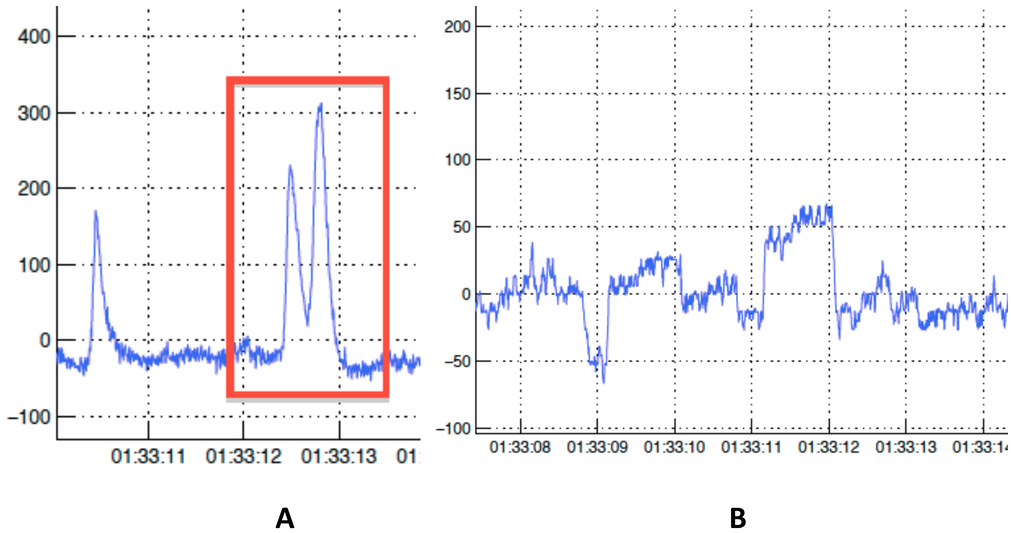


Figure 4.25: Double blink, (A) vertical channel, (B) horizontal channel.

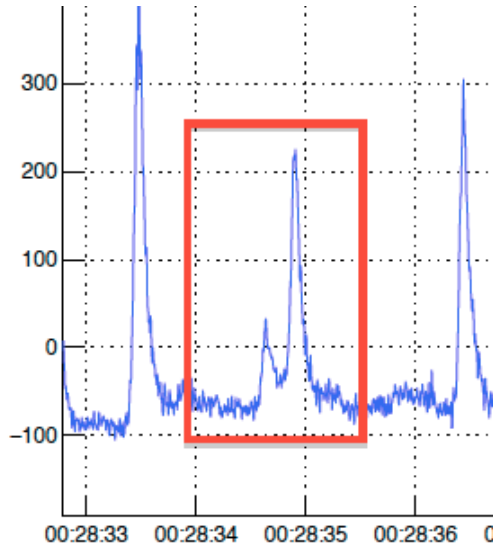


Figure 4.26: Double blink on EOG

4.6.2 Combination

Some waveforms in the EOG data are combination of different kinds of basic waveform types. These combination signals are difficult to identify by just look at the EOG signal.

Fast Central Rearview Mirror Checking

The driver briefly checks central rearview mirror and two blinks appear very close to each other. If we only look at the vertical channel, the EOG signal is similar to double blink. The

only way to distinguish this kind of blink to double blink is to check the horizontal channel. The significant rise in the horizontal channel indicates that the driver turn his/her eyes to right.
Examples:

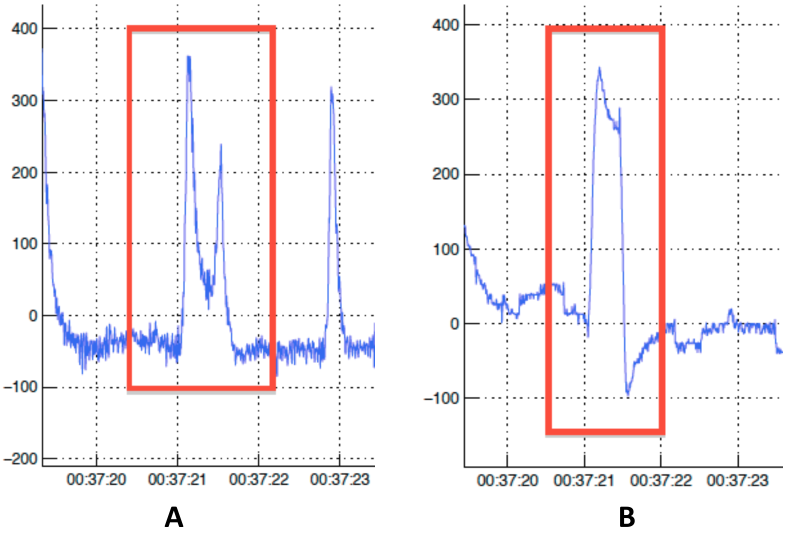


Figure 4.27: Two blinks combination, (A) vertical channel, (B) horizontal channel

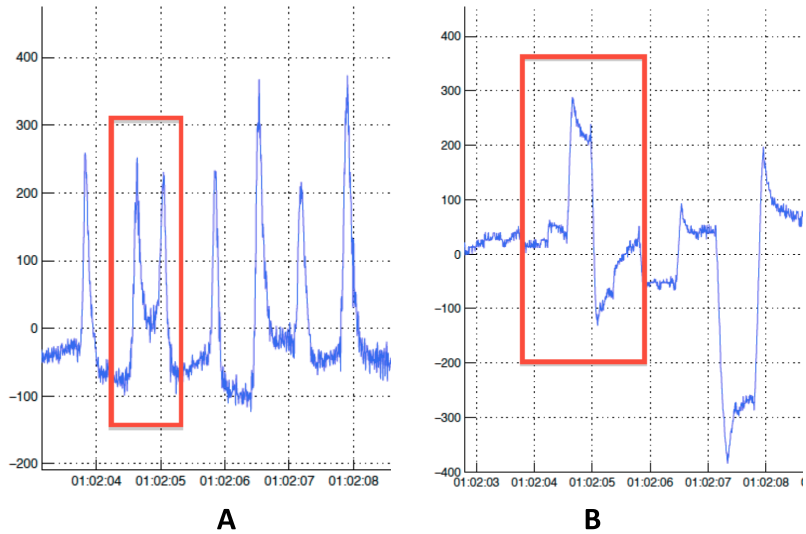


Figure 4.28: Two blinks combination, (A) vertical channel, (B) horizontal channel

Rearview Mirror Checking Combination

When the driver tries to overtake other vehicles, he/she needs to check the different rearview mirrors one by one. The most common situation is to check the central mirror first and then checking the left side mirror. The driver's viewpoint will change from the central mirror directly to the left side mirror.

In figure 4.29, the driver turns his viewpoint from the front window to the central mirror at the time 00:28:21, where a normal blink pattern appears at the beginning. At 00:28:22, another blink appears and from the horizontal it's very clear that the EOG signal change from 200 μV to -200 μV. This is because the driver changes his viewpoint from right side of his body to the left side to look at the left side mirror. The whole procedure ends with a normal blink pattern in vertical before the time 00:28:23.

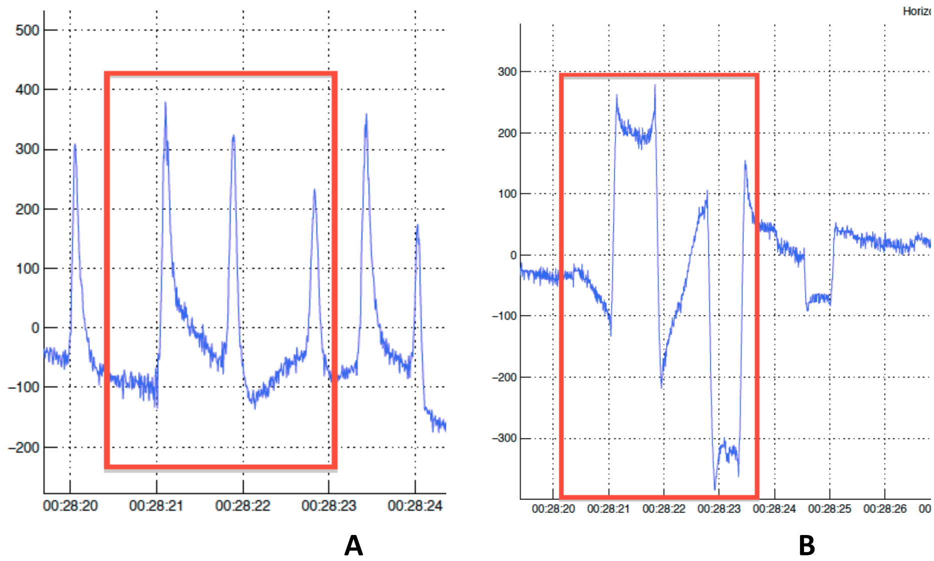


Figure 4.29: Two-rearview mirror checking combination, (A) vertical channel, (B) horizontal channel

4.7 Long blink

Long blink refers to a blink that has duration longer than 500 ms. It's difficult to distinguish these kind of blinks in the video record, but from the EOG signal, we can still find some examples. Long blinks are usually found at the night driving test session when the participant becomes drowsy. It's believed to be related with the driver's alertness state becoming lower, therefore it can be very useful in the measurement of the driver's drowsiness level.

Figure 4.30 to 4.32 shows three examples of long duration blink. Figure 4.32 gives an example of when the double blink becomes longer than a normal blink. The amplitude of the blink is also reduced to around 100 μV. The duration of this blink exceeds 1 second.

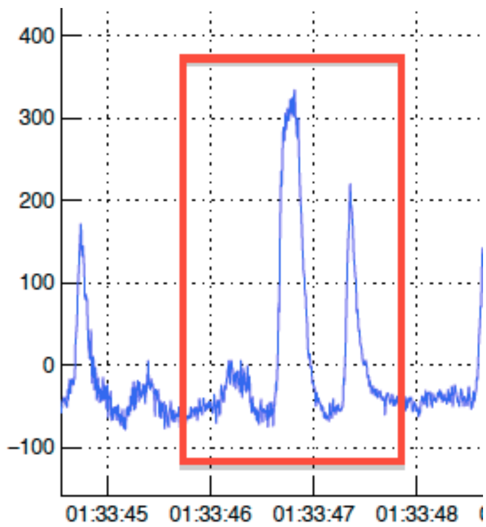


Figure 4.30: Long blink, vertical channel.

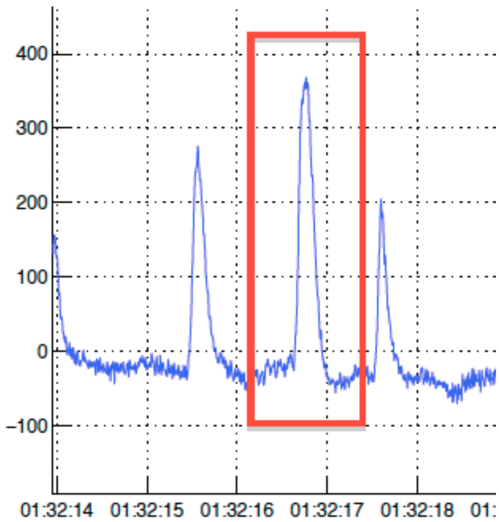
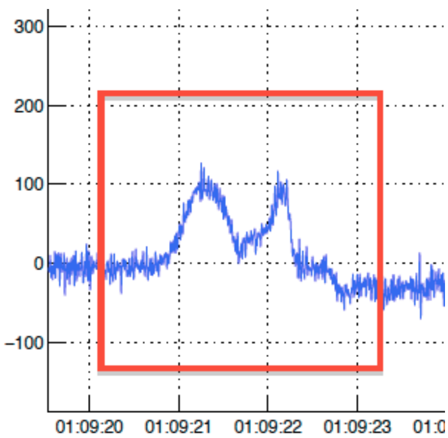
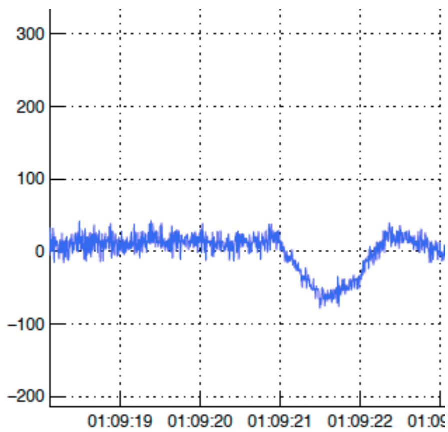


Figure 4.31: Long blink, vertical channel.





A **B**

Figure 4.32: Long blink, (A) vertical channel, (B) horizontal channel

5 Blink Detection Algorithm

In a previous work, blinks were detected based on the analysis of the vertical EOG signal and to characterize the vertical movements of eyelid (Jammes, 2008). The velocity of EOG waves was used as the indicator to find blinks. This chapter suggests how the knowledge gained in the EOG library can be used to improve this detection algorithm,

5.1 Previous Algorithm

The first step of this algorithm is to filter one of the vertical channels of the EOG in order to remove high frequency noise.

Secondly, the derivate of the EOG data differentiated by

$$\frac{dEOG}{dt} = \frac{EOG\big((k+1)\cdot T\big) - EOG(k\cdot T)}{T}$$

Step three is locating some 'events' in the EOG velocity data, which may be considered as a blink movement candidate. The criteria are to find out those events that have EOG velocity increase above a specific value Vcl (the threshold of eyelid downward velocity) and followed by a period below value Vop (the threshold of eyelid upward velocity).

The fourth step is to validate the amplitude and duration of the events. If an event has duration longer than 0.5 seconds and the amplitude of the closing and opening phase greater than a threshold value Amin, the event is consider as a valid blink.

The last step will verify the events that failed to reach the previous step if there is a contiguous event present (double blink). Such events will be merged together and checked again.

This algorithm in detecting blinks in EOG signals shows an acceptable result. However, some blinks are missing (false negative) and some extra blinks are detected (false positive). This algorithm may also ignore the long blink that has very slow eyelid movement velocity; meanwhile, the blinks accompanied with the driver's viewpoint change (check dashboard or rear view mirror) may be counted as a valid blink. In this project, these issues are the problems we are trying to solve by designing and a more reliable method to detect blinks.

5.2 Possible Improvements

Based on the literature survey and on the knowledge gained from the EOG dictionary, a number of improvements can be made to increase the robustness and reliability of the blink detection algorithm. The first few steps of EOG processing are similar to the old algorithm, which is focusing on filtering the raw signal and find out if candidate events are not considered here. In order to improve the accuracy of the blink detection, we need to employ some achievements acquired from the EOG library and apply to the last step of the algorithm. The last part of this algorithm is to remove the strange blinks and blinks not related to the driver's alertness status. The candidate blinks that have too long or too short durations will be excluded. Events with duration less than 50ms are usually produced by small range of eyeball rotation while events with duration longer than 1000ms generally indicate that the event is related with face muscle movements. There are some candidates with larger opening velocities than closing velocities or the amplitude before the blink and after has a large difference. From the EOG library studies we know the activities in the EOG signal are related with head movements or driver changing his/her viewpoint from front window to other places. Therefore, these activities are not related with the driver's alertness status either, they need to be removed.

5.2.1 Blink Amplitude and Velocity

In chapter 2 when discussing blink variables in the EOG signal, we mentioned the relationship between blink amplitude and its velocity. This relationship can be used to identify strange blinks and improve the accuracy of the blink detection.

In this approach, first we need to plot the amplitude-velocity relationship similar to figure 5.1. Each point in this figure represents an individual event, and the information of each event is acquired from the first step of the algorithm. Then we can find out a linear function between these two variables. The central line in figure 5.1 shows the best fitting regression line for all data. The dashed lines contain at least 95% of all data. Therefore, if a point in figure 5.1 is found far away from the dashed lines range, it indicates that this event might not be considered a spontaneous blink. Figure 5.2 is the example we gave in chapter 4 to show how the EOG signal appeared when the driver checked the dashboard. In this case, when search the EOG signal amplitude for the onset point of the blink by looking for local minima, the red circle will be a possible start point. However, by put this event into the velocity-amplitude relation graph, it will be outside the confident interval. Because the amplitude difference between red circle and yellow circle is around 200 μv larger than the normal blink of such a velocity. We can either move the start point to the black circle or ignore this event. As we mentioned in chapter 4, this blink is companied with dashboard checking, therefore it is not related with driver's alertness status and it's better to ignore it. We can also apply this method to up-phase of blinks to improve the accuracy of blink end point.

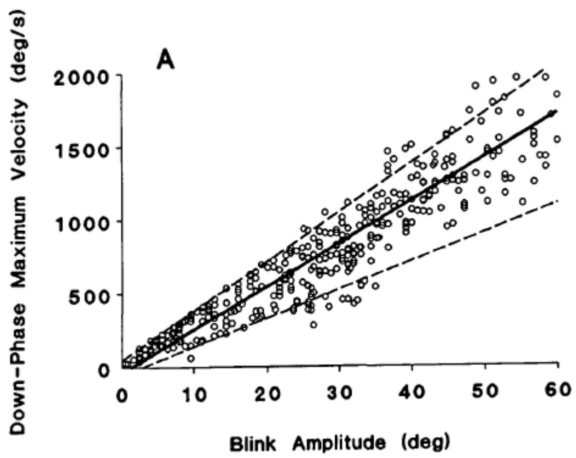


Figure5.1 Relationship between down-phase eyelid maximum velocity and blink amplitude

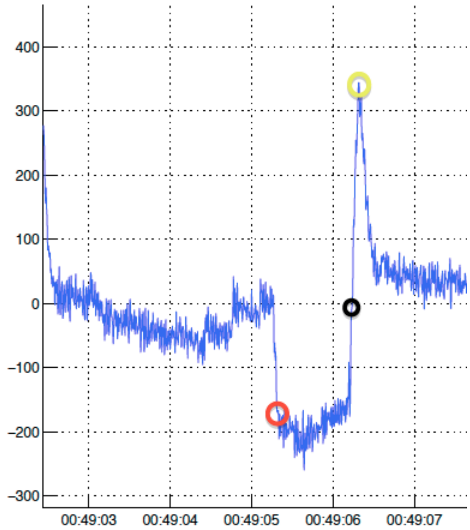
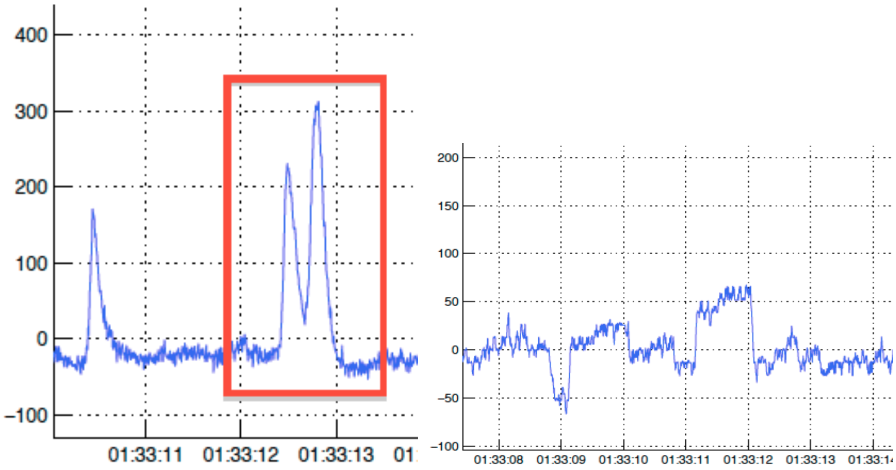


Figure 5.2 Dashboard checking EOG signal

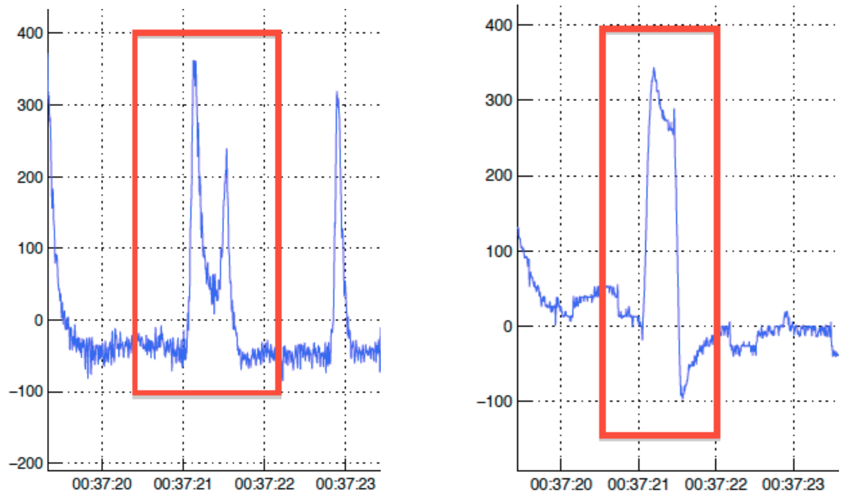
5.2.2 Horizontal Channel Information

The previous algorithm only uses the vertical channel of EOG signal to detect blinks. When we collected the EOG data with measurement instrument we also get the horizontal channel data. Obviously the blink behavior itself only can be seen in the vertical channel, but when building the EOG library, we found that horizontal channel signal also contains important information. Horizontal channel data can help us in identifying some strange signals in the EOG. Such strange signals usually are considered as blinks if we only look at the vertical channel.

We can a median filter to smooth and remove the noise in the horizontal channel. Figure 5.3 is an example of a double blink complex in the EOG signal. As mentioned in that section, the driver is blinking twice in a short time (around 500 ms). From the horizontal channel we can see there is no significant change in the EOG amplitude. In this situation, we can consider it is as normal spontaneous blink. In Figure 5.3 A, the EOG signal represents the fast central rearview mirror checking made by the driver. The vertical channel graph in Figure 5.3 B looks very similar to Figure 5.3 B. If we only consider vertical channel in this case, the rearview mirror movement can be explained as a blink, but actually the blink-like shape in Figure 5.3 A is brought out by a saccadic eye movement. Once we refer to the horizontal channel, an obvious difference can be seen. The central rearview mirror is not directly in front of the driver, so when the driver check it he or she must turn the viewpoint a bit right. This action transfers into a constant high amplitude in horizontal EOG channel. When a double-blink is detected from the vertical channel, we can first calculate the derivate of horizontal signal and set velocity threshold for turn left and turn right. If the eye movement velocity in horizontal channel is beyond these thresholds, the blink is related with saccadic eye movements and is hence not spontaneous.



A



B

Figure 5.3 Similar vertical channel EOG signal for different situation, A (double blink), B (fast central rearview mirror checking)

This method can be used for identifying other actions when the driver turns his/her viewpoint horizontally. Once an unsure event is detected we can check the horizontal channel. If a significant change (view point turn left or right) is found in horizontal channel is found, we can classify these events as in saccadic eye movement blinks.

5.2.3 EOG Amplitude Variation

When we investigated the EOG signal on a larger scale we found another transformation trend in the driving test. Figure 5.4 shows the vertical channel EOG signal of a participant during a daytime driving test. We zoom out the graph and can see the whole test data. The test lasts about 5000 seconds. Since there is not too much action can make the EOG signal amplitude larger than the peak value of a blink, we can assume the majority of the amplitudes are contributed by blinks. From figure 5.4 it's clear that the average peak value of blink is around 400 μV. The amplitude keep steady from the beginning till the end of the test. Figure 5.5 is the vertical channel EOG data from same participant when he took the night driving test. Obviously, the amplitude of night driving changes from 400 μV to less than 200 μV. The amplitude decrease with time, and this phenomenon could also be found in other participants' data like figure 5.6 and 5.7.

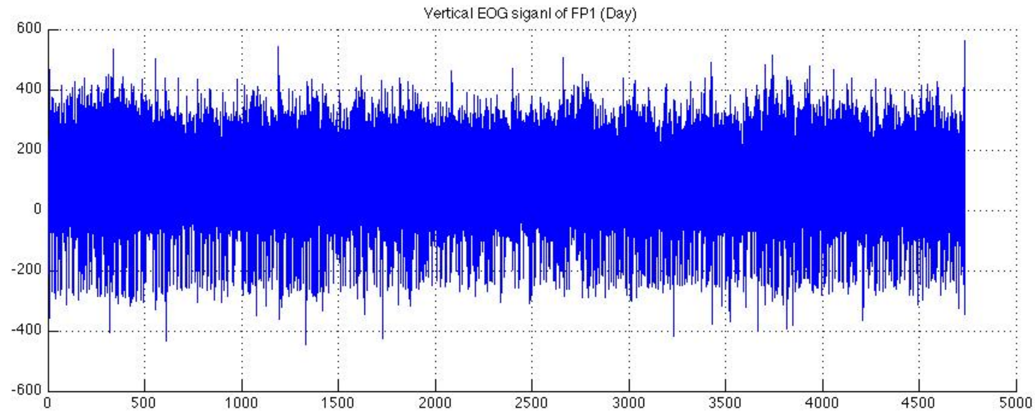


Figure 5.4 The whole EOG data of FP01, daytime test, vertical channel

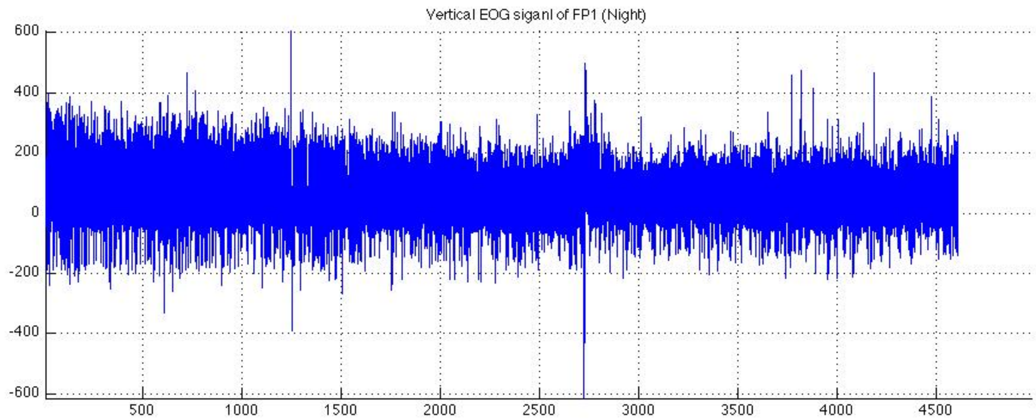


Figure 5.5 The whole EOG data of FP01, night test, vertical channel

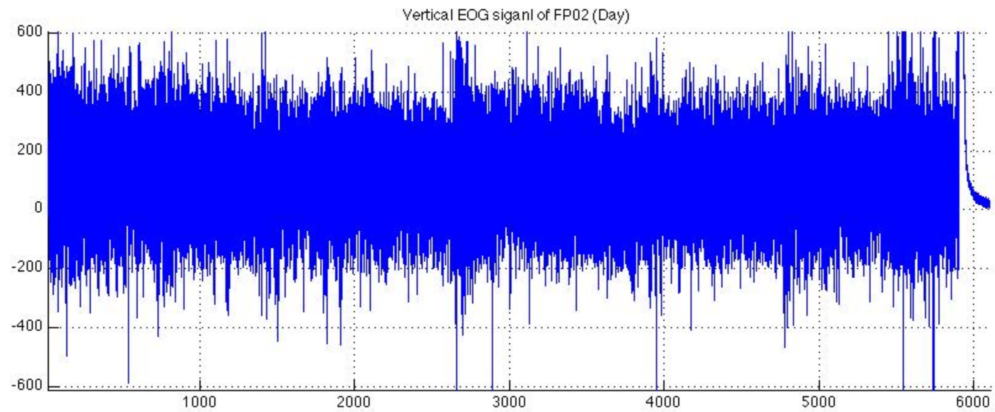


Figure 5.6 The whole EOG data of FP02, daytime test, vertical channel

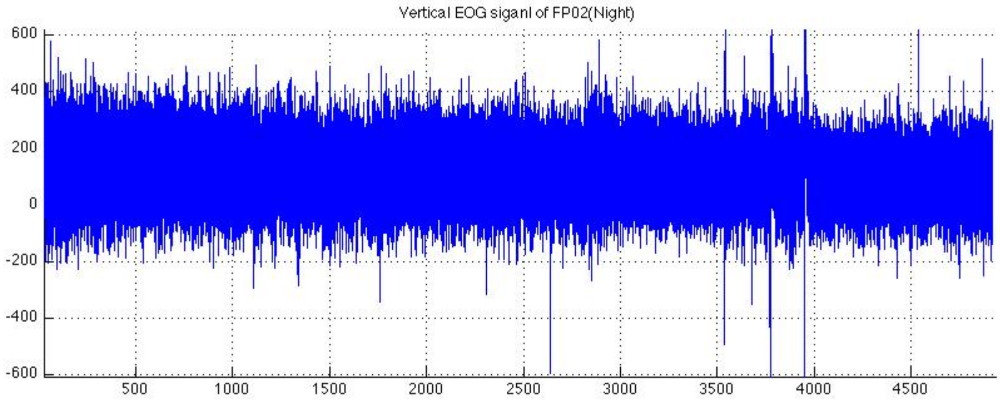


Figure 5.7 The whole EOG data of FP02, night test, vertical channel

In table 5.1 and 5.2, we list the blink amplitude and number changing trends of 9 participants. We split the whole test session into 3 stages, each stage contains 1500 seconds. The blink peak amplitude and total blink number were counted separately from each the three stages. 7 of those test drivers shows decreased blink amplitudes at the night driving test, however there is no evidence that the number of blinks change with the driver's alertness state. 5 people shows decreasing number of blinks while the other 4 are increasing or keep steady during night test. In daytime test, 4 of the driver's data appear decreased in blink amplitude while others were kept steady or increased. The amplitude decrease level at night test session range from 4% till 30%.

	Day Time Test			Night Test		
Participant	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
FP01	263	249	238	218	165	152
FP02	307	277	282	308	281	261
FP03	219	226	230	215	253	259
FP07	261	225	209	182	169	165
FP10*	238	220	233	249	215	225
FP11	348	366	364	384	414	420
FP12*	289	295	283	338	332	344
FP13*	217	179	158	192	176	163
FP15	533	532	531	478	476	457

Table 5.1 Average blink amplitude during different test stages. Each stage lasts 1500 seconds. *Due to insufficient data, these participant's data were split into different stages. FP10, stage length=800s; FP12, stage length=900s(Night); FP13, stage length=800s(Night).

	Day Time Test			Night Test		
Participant	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
FP01	1083	1055	1174	787	852	854
FP02	1350	1360	1342	1112	1224	1324
FP03	536	528	613	628	597	586

FP07	931	871	861	594	717	680
FP10*	1253	1172	1302	478	494	390
FP11	708	883	969	741	622	600
FP12*	562	593	519	295	290	326
FP13*	936	872	842	343	275	346
FP15	1377	1331	1340	1372	1344	1331

Table 5.2 Blink number during different test stages. Each stage lasts 1500 seconds. *Due to insufficient data, these participant's data were split into different stages. FP10, stage length=800s; FP12, stage length=900s(Night); FP13, stage length=800s(Night).

From the discussion above, we bring out a hypothesis that the amplitude of the vertical EOG signal is related with the participant's alertness level in some way. In the daytime driving test, the driver's alertness condition at the end of the test is more or less the same as the beginning. But during night test, the driver became drowsy after driving for a while. In pervious sections we mentioned the linear relationship between blink amplitude and blink velocity. The amplitude will decrease with low velocity blink. Previous experience also demonstrated that blink duration could increase when people become drowsy. All these facts explained what we discovered here about the blink amplitude. When the participant's alertness level decreases, the more long duration blink appears, and these blinks have long duration and low velocity. Therefore, the amplitude of blink will be lower than normal blink and the average amplitude will decrease with more and more such blink appears. With this hypothesis we can use not only blink duration but also the average amplitude of vertical EOG signal as the indicator of the driver's alertness level. But before we use it there are some problems that need to be solved. First of all, we realize that different participants have different average amplitudes. So we can't set one particular threshold for the vertical channel as an indicator of drowsiness. Secondly, since the amplitude changes continuously, we need to handle a long-term EOG record to say if it's decreased. Some participants' data show that even at the beginning of night driving test, they already have lower amplitude compare with the daytime test. Therefore, we need the daytime data as a reference standard, if the average amplitude deviate from reference to a certain level, we can tell that the participant is about to become sleepy. The change in blink frequency trends seems blurred here, but there is still a possibility that the blink frequency is related to drowsiness. The relationship between blink number and other blink variables need further research.

6 Discussion

This chapter summarizes the achievements of this project. Discusses the problems found during this project, as well as the possible future research directions.

6.1 Effect of the blinks on saccades.

The EOG library in chapter 4 gives us efficient help to improve the blink detection results. Previously some EOG signals were considered as spontaneous but with construction of the EOG library we found that these signals were actually brought out by vertical saccades or eye-head gaze shift. For example when the driver checks the central rearview mirror, he or she need to focus the view from straight forward to the upper place of the car's front window. This saccadic eye movement lasts for approximately 0.02 to 0.1 seconds and is usually accompanied by blinks. Previous research shows that the blink will affect the dynamic properties of saccades (Rottach, 1998), but we don't know whether the blink parameters will change with the saccades. If the blink on saccade has a different profile compared to spontaneous blinks, we need to give more attention to such blinks when we want to extract the driver's alertness condition through these signals.

6.2 Blink frequency

As seen in section 2.3.1, when a participant is focusing on some task that requires close attention (e.g. reading), the blink rate decrease. The attention required for driving is not comparable to reading, but sometimes when complex situations happen on the road it also needs the driver to pay a lot of attention and therefore the blink frequency could decrease a little in comparison with a completely relaxed situation. On one hand concentration and focusing can depress the blink frequency as we have discussed so far, on the other hand, long time driving on highway can increase the fatigue level of the driver and the blink rate may increase, some studies have reached the conclusion of this phenomena (Johns, 2007; Andreassi, 2000). Blink frequency and duration both increase when the driver becomes drowsy. Combined with the physiological knowledge of the blinking control system, drowsiness is in some way loosening the whole blinking reflex path by slowing down the blink reflection. Another study shows that the blink rate may either increase or decrease when the participant becomes drowsy (Stern, 1984). But one thing is confirmed that the proportion of long duration blink increase with the driver's lower alertness level. If we are interested in the driver's alertness states, we shall not only monitor the blink frequency, but also give attention to the appearance of long duration blinks. One possible solution is giving some weighting for different blinks. We can judge the driver's alertness states by calculating the blink frequency, and give a higher weight for long duration blinks.

6.3 Double blink as indicator

Another important factor we should pay attention to are the double blinks. These blinks also usually appear at the end of the driving test when the driver becomes drowsy. It's an incomplete ‘blink’ followed with a complete long blink. From the video record we found the driver’s eyelid move downward for a little and rise up, immediately after this movement the eyelid performs a complete down-phase and up-phase blink. In the previous algorithm to detect blinks, we consider this kind of blink as a long blink. But this kind of eyelid movement is an obvious indicator of drowsiness. We think the double blink should be isolated from other blinks and used as an important flag for drowsiness independently.

6.4 Future development

Since we acquired information about how to interpret EOG signal, we can apply this knowledge to the eye tracking drowsiness monitor system, compare the onboard drowsiness detect result with the EOG analysis result. The EOG data can also help when developing the algorithm to determine the driver’s alertness states by analyzing eye-tracking data. In the future development, we can continue with these areas:

- It is very important to find out the critical point when the driver’s alertness state is just becoming worse than safety threshold. This requirement will bring out two issues to doing research: first, what is the safety alertness condition for a driver driving on highway? Second, how can we find out the critical point with an eye tracking system?
- Different people have different physiological condition; we may start the algorithm by collecting data when the driver’s alertness condition is fully alert. A model can be built based on the data we acquired so far and establish a judgment criteria once the driver become drowsy enough and the psychological indicator such as blink frequency and duration deviate from fully alter state by too much, we deliver a warning to the driver.
- A problem may rise when the driver entering the car is already too drowsy to drive. Therefore, we need to employ some other assistant sensor to monitor like steering wheel deviation. Integrate eye tracking with other drowsiness indicator can give a better overall performance.

6.5 Conclusion of The Project

In chapter one, we listed the following aims of this project:

- Study of the physiological principle of blinks and the relationship between blinks and the EOG signal as well as the relationship between drowsiness and blinks.
- Interpret the on-road driving test EOG data in detail, and find out the origin of some particular events in the EOG data.
- Build an EOG library containing enough information for different kinds of EOG waveforms, especially related with blinks. Give literature explanation on the appearance and formation reason of those signals.
- Improve the blink detection algorithm.

From the literature study of this project we explored the previous research in eye blinks and eye movements. Summarizing this knowledge we obtained some important ideas for next steps to study the EOG and blinks. Information such as blink duration and amplitude support this work in improving the blink detection algorithm.

While building the EOG library, we analyzed the EOG signal more thoroughly by comparing each typical signal with the driving test video, to give better interpretations and descriptions for the signals. The procedure of EOG library construction also helped us to understand the EOG signal better. The EOG library covered basically all the possible signals that could appear during a driving test. The explanation and illustration of different EOG waveforms provide fundamental material for improving the blink detection algorithm.
Analyzing the EOG library and the results from the literature study resulted in an improvement of the blink detection algorithm.

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Appendix

Matlab codes preprocessing and plot the EOG signal:

A1. Main part of the codes

```
%EOG signal analysis
%Chongshi Yue
%LiU 2011
clear all;
close all;
clc

load fp01_d_vh.mat;
load fp01_d_h.mat;

%% Resampling
eogv=fp01_d_vh;
eogh=fp01_d_h;
Fs=256;
%change the smaple frequency
eogv_n=resample(eogv,Fs,512);
eogh_n=resample(eogh,Fs,512);

%% Baseline remove
 FO = 5;           % Order of filter
 FC_H = 0.7/(Fs/2); % Cut-off frequency for Baseline wandering removal filter
 FC_L =40/(Fs/2);   % Cut-off frequency for Low-pass Butterworth filter
 [x y] = butter(FO,FC_H,'high'); % High-pass Butherworth for baseline drift removal
 eogv_n = filtfilt(x,y, eogv_n); % Removes baseline shift using forward-backward fitring

%% Synchronize time vector with video time

ts=datenum('00:47:17'); %set start time point
tf=datenum('02:06:15'); %set finish time point
t=linspace(ts,tf,length(eogv_n));



%% Plot vertical channel
figure(1)
grid on;
hold on;
plot(t,eogv_n);
title('Vertical EOG siganl of FP01 (Night)');
```

```
xlabel('Time[s]');
ylabel('Potential[uV]');

% change x-axis to date form
tp=linspace(ts,tf,(length(eogv_n)/Fs));
set(gca,'xtick',tp);
for n=1:length(tp)
tm{n}=datestr(tp(n),'HH:MM:SS');
end
set(gca,'xticklabel',tm)
hold off;

%% Plot horizontal channel
figure(2)
grid on;
hold on;

plot(t,eogh_n);
title('Horizontal EOG siganl ')

%change x-axis to date form
tp=linspace(ts,tf,(length(eogv_n)/Fs));
set(gca,'xtick',tp);
for n=1:length(tp)
tm{n}=datestr(tp(n),'HH:MM:SS');
end
set(gca,'xticklabel',tm)
hold off;

%% Split Vertical EOG into 3 segments
 tv=0:1/Fs:(length(eogv_n)-1)/Fs; %New time vector
 eogv_a=eogv_n;
 eogv_a(find(eogv_a<0))=0;
 eogv_a1=eogv_a(1:(256*1500));
 eogv_a2=eogv_a((256*1500+1):(256*3000));
 eogv_a3=eogv_a((256*3000+1):(256*4500));

%% Caculate Blink Amplitude
 amp1=EOGamp(eogv_a1)
 amp2=EOGamp(eogv_a2)
 amp2=EOGamp(eogv_a3)
```

A2. Codes for calculate average blink amplitude and numbers

```
function EOGamp = EOGamp(EOG)
Fs=256;
tv=0:1/Fs:(length(EOG)-1)/Fs; %New time vector
Thres=60;  %Set Threshold
B_pos=[];  %Blink peak position
% N_s=length(EOG);
n=1;
Amp=0;      %Totla Amplitude

[Amp,B_pos]=findpeaks(EOG,'minpeakheight',80);

%Remove fake peaks
B_pos_n=[];
B=1;

for n=1:1:(length(Amp)-1)
if B_pos(n+1)-B_pos(n)<128
   if Amp(n)>Amp(B)
      B=n;
   end
else
   B_pos_n=[B_pos_n,B];
   B=n+1;
end
end

Amp=Amp(B_pos_n)';
B_pos=B_pos(B_pos_n)';
Blinknumber=length(B_pos)
br=robustfit(B_pos,Amp)

%Plot Blinks
figure()
plot(tv, EOG); hold on,
plot(tv(B_pos), EOG(B_pos),'ro','markersize',10);
plot(tv(B_pos),br(1)+br(2)*EOG(B_pos),'g','LineWidth',2); hold off,
legend('EOG ','Blink','Robust Regression');
title('Blink Detection');

EOGamp = mean(Amp);
```