# *CAN FREQUENCY DOMAIN HEART RATE MEASURES DETECT IMPAIRED DRIVER PERFORMANCE?*

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**Summary:** An overnight driving simulation scenario with partial sleep deprivation was utilized to induce driver performance impairment. Heart rate (HR) was recorded over the entire experiment; frequency domain HR measures were derived and correlated to variation of lane deviation (VLD), a driving performance measure, and to the driver's state, which was estimated by the Karolinska Sleepiness Scale (KSS). The aim of this study is to evaluate whether frequency domain heart rate measures can be used to detect impaired driver performance as well as reduced driver state. We generalize the concept of the conventional frequency domain HR measures – namely the very-low frequency (VLF), low frequency (LF) band and high frequency (HF) band – into finer-grained frequency bands of 0.02 Hz width. These newly defined frequency bands show a more detailed correlation to driving performance and to driver sleepiness state, taking subject-specific differences into account.

## INTRODUCTION

In this work, we focus on the correlation between *heart rate measures* from the *frequency domain* and *driver performance* as well as *driver sleepiness state*, using data from five subjects. Driver performance is the result from a combination of the driver state and task demand (Brookhuis & De Waard 2001). During the driving task, operators experience a certain state of mental workload and a changing level of fatigue, which is reflected through changes in performance, *heart rate* (HR, number of heart beats in a specific time period) and *heart rate variability* (HRV, phenomenon of varying time durations between heart beats). Therefore, impaired driving performance should be detectable by HR measures in general. A correlation between driver performance, driver state and specific HR measures can be expected.

In a previous report (Hefner et al. 2009), we analyzed driving performance based on the driver fatigue state using data of one subject. We showed that multiple sleepiness and driving performance measures correlate well with different expressions of heart rate variability (HRV), especially with long-term HRV (Heinze et al. 2011). Driving performance can diminish to a degree that accidents are the result. The reason for accidents in many cases is the fatigue state of the driver. The risk of driver fatigue was assessed in Moore-Ede et al. (2004). Driver fatigue is one important component responsible for impaired driving performance, but not the only one: Increased mental workload can decrease driver performance as well.

Brookhuis & De Waard (2001) discussed extensively the sensitivity of the frequency band around 0.1 Hz to mental effort. They point out that the 0.1-Hz frequency component of HR is insensitive to compensatory effort caused by driver sleepiness, but sensitive to computational effort caused by task load. This opens the possibility to separate the two components of driver performance. For this purpose, we generalize the concept of the conventional frequency domain measures such as *very-low frequency*, *low frequency*, and the *high frequency band* and introduce *smaller frequency bands of 0.02 Hz width*. These fine-grained frequency bands show a more detailed correlation to both driving performance and driver sleepiness state. Additionally, they allow investigating subject specific differences in greater detail. This is essential because individuals differ in their ability to perform under different driving conditions. The idea of smaller frequency bands were introduced by Chua et al. (2012) with interesting results. From the correlation differences between relative power spectral density (PSD) of the fine-grained frequency bands on one hand and the *Karolinska sleepiness scale* (KSS) and *variation of lane deviation* (VLD) data on the other, important conclusions about the separation of driving performance and driver sleepiness state should be possible.

## DATA COLLECTION

The study was conducted by the Research Group of Adaptive Signal Analysis at the University of Applied Sciences in Schmalkalden, Germany. The study consisted of overnight driving simulations. Before the experiment nights, subjects were trained in driving and the different tests. They carried an activity monitor and completed a sleep/wake log for at least 24 hours prior to the experiment. Subjects arrived at the lab at 10 pm. After wire-up, checking logs and activity monitors, and retraining, experiment sessions started at 11:30 pm. There were eight experiment sessions, each lasting one hour, and the last session finished at 8:30 am. The subjects had a 1-h break at 3:30 am. Each session included a 40-minutes driving task, a 10-minutes compensatory tracking task, and a 5-minutes psychomotoric vigilance test. Five subjects participated each in two experimental nights. Only the heart rate measures, the subjective sleepiness KSS and the driving performance, expressed as variation of lane deviation, are discussed here. The driving situation reflected a night time driving experience that was designed for minimal mental workload: the driving lane through a rural environment consisted only of straights and wide curves with no intersections; there was no traffic and no secondary task.

## DATA ANALYSIS

### Driving Performance Measure

During each 40-minute driving session, the *lateral driving lane deviation* was continuously recorded. As an objective measure of driving performance, the *variation of lane deviation* (VLD) was calculated over the entire driving session. The driver performance measure can be considered as a combination of driver state and task load.

### Driver State Measure

The *Karolinska sleepiness scale* (KSS) is a standardized, subjective and independent measure of sleepiness on a numeric scale between 1 and 10, which was introduced by Åkerstedt & Gillberg

(1990). It was utilized to reflect the driver's sleepiness state. The KSS was noted in four-minute intervals during each driving session; then the average per driving session was calculated.

## Heart Rate Measures

Heart rate measures were derived from the electrocardiogram (ECG) recordings by detecting the position of R-peaks (i. e. heart beats) in the ECG and calculating the time interval between consecutive beats. This results in the so-called *RR time series* with characteristic time and frequency contents, which is the basis for the heart rate measures in the frequency domain. The heart rate (HR) itself and the heart rate frequency measures used here were calculated using a five-minute moving window with time steps of one minute. In the frequency-domain, the *power spectral density* (PSD) of the RR time series was calculated using the fast Fourier transform (FFT). Based on the PSD result, the power values for different frequency bands were derived. The commonly used standard frequency bands are *very-low frequency* (VLF, 0-0.04 Hz), *low frequency* (LF, 0.04-0.15 Hz), and *high frequency* (HF, 0.15-0.40 Hz). All three frequency bands were normalized by the total power. In addition, a more detailed frequency analysis based on *0.02-Hz bins from 0.0 to 0.40 Hz* was conducted, similar to the approach proposed by Chua et al. (2012). The 0.02-Hz frequency bands were normalized by total power as well. The usage of relative or normalized PSD for the frequency bands leads to different results than those obtained by absolute PSD (Chua et al. 2012).

## Comparison of heart rate measures with driver performance and driver state

All session values were normalized using maximum-minimum scaling on a subject-by-subject level; this mitigates the individual differences between the subjects and makes the data comparable. Then, all of the data was averaged over all 5 subjects. The KSS, VLD and the HR were plotted for all sessions over both trials (figure 1a). Similar plots are shown in figures 1b-d, replacing the HR successively with the classical frequency bands VLF (figure 1b), LF (figure 1c), and HF (figure 1d). Correlation coefficients between individual HR, frequency domain measures and driving performance (expressed by VLD) and driver state (expressed by KSS) were computed. The correlations are based on the averaged data over all 16 sessions (8 sessions per trial × 2 trials). Finally, subject-specific (figures 2a-e) and overall (figure 3) correlations were computed by pairing session values of each 0.02-Hz frequency band with respective session values of driving performance (VLD) and driver sleepiness (KSS). Correlations were considered significant for p-values $< 0.01$ (*).

## RESULTS

As seen in figures 1a-d, the average driving performance (VLD, black bars) and average driver sleepiness state (KSS, red curve) show a time-on-task and a modest time-of-day behavior. Performance impairment and sleepiness are low during the first four sessions and significantly higher during the last four sessions. Maximum performance impairment and sleepiness occurs during the 6th and 7th session between 5:30 and 7:30. The course of the KSS is very similar for both nights. This result is quite different from the VLD result, where the performance impairment is stronger in the second night.

Figure 1a displays HR (green bars) together with KSS and VLD. The first important thing to notice is that average HR itself does not correlate well with driver sleepiness state or driving performance. However, the correlation between HR and KSS is stronger than the correlation between HR and VLD. It is well known from previous work that HR in beats per minute is decreasing with higher sleepiness (Chua et al. 2012) and increasing with increasing mental workload (Mehler et al. 2011).

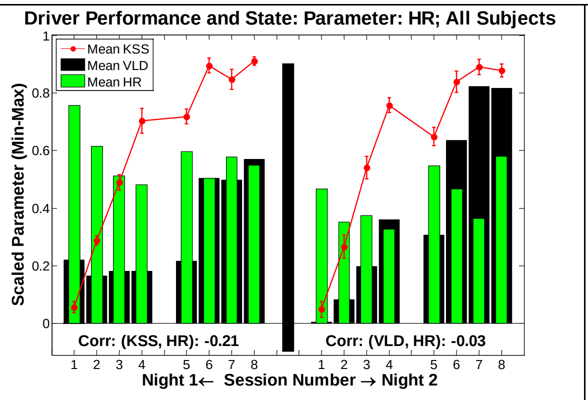


**Figure 1a. KSS (red line), VLD (black bars), and HR (green bars) as a function of the session number. All parameters are scaled**

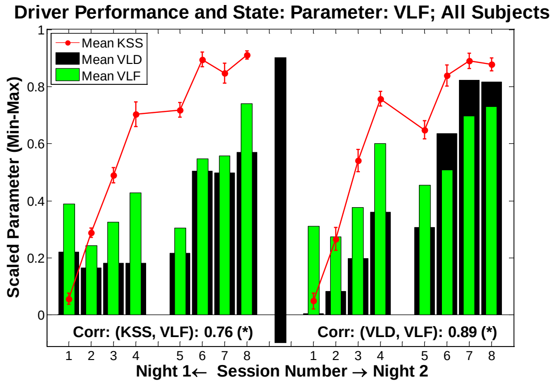


**Figure 1b. KSS (red line), VLD (black bars), and relative PSD of the VLF frequency band (green bars) as a function of the session number. All parameters are scaled**

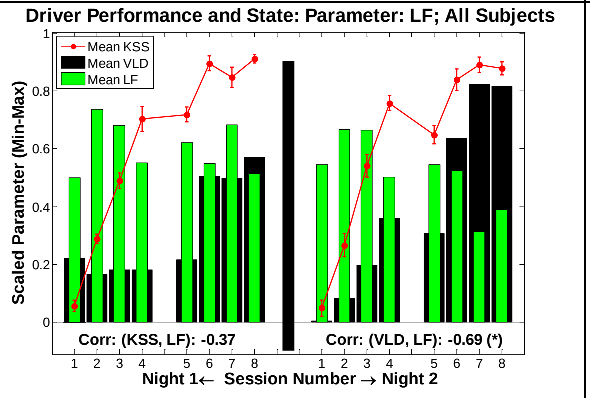


**Figure 1c. KSS (red line), VLD (black bars), and relative PSD of the LF frequency band (green bars) as a function of the session number. All parameters are scaled**

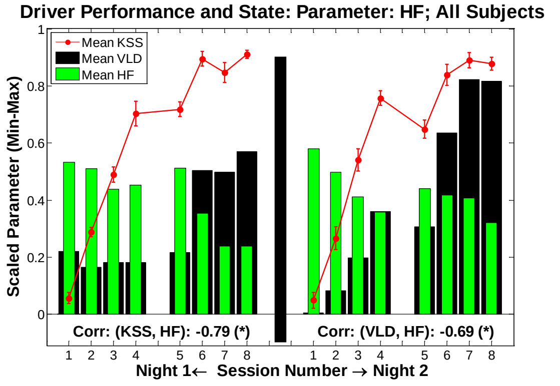
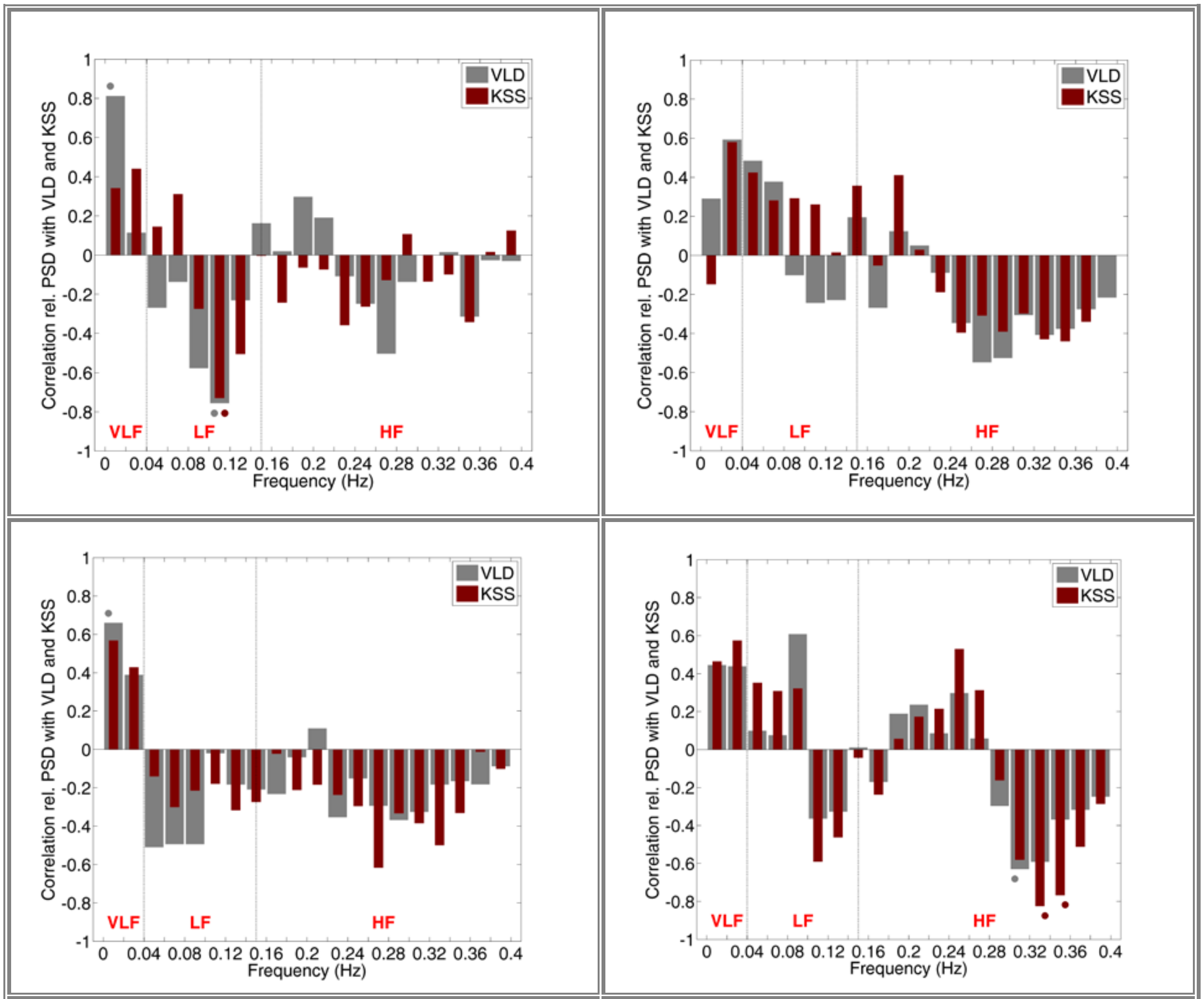
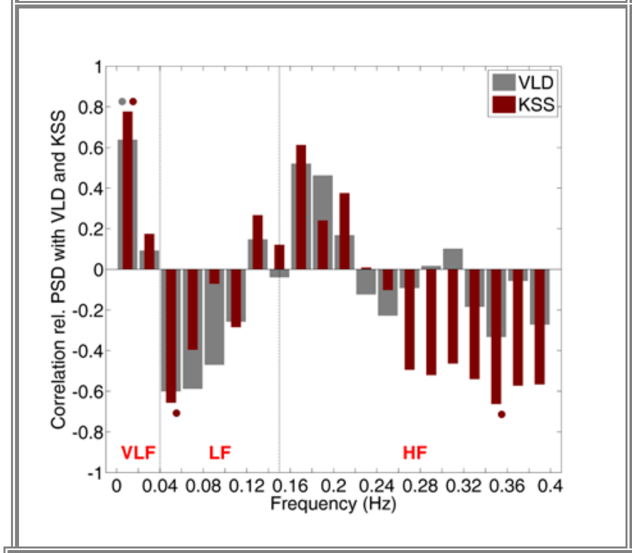


**Figure 1d. KSS (red line), VLD (black bars), and relative PSD of the HF frequency band (green bars) as a function of the session number. All parameters are scaled**





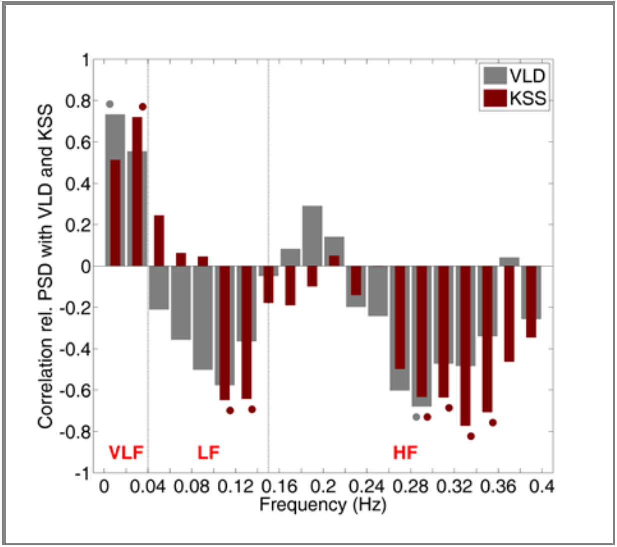


**Figure 2a-e. Subject 1-5 specific correlations of relative PSD for the small frequency bands with KSS (red bars) and VLD (grey bars). Dots indicate the correlation significance for $p < 0.01$ (*)**

**Figure 3. Mean correlations over all subjects of relative PSD with KSS (red bars) and VLD (grey bars). Dots indicate the correlation significance for $p < 0.01$ (*)**

Another indication of this is expressed through the weak negative correlation of -0.21 between

KSS (increasing) and HR (decreasing). There is no correlation (-0.03) between HR and VLD. This is quite intriguing because the impaired driving performance (higher VLD) is caused by increased mental workload and increased sleepiness. Both increases are influencing the HR in opposite direction, canceling out any effect of driver performance on HR. For the standard frequency bands the correlations with VLD and KSS are changing in a very consistent way. KSS (0.76*) and VLD (0.89*) significantly correlate with the PSD of the VLF band over the course of the driving sessions (figure 1b). The higher correlation of VLD can be explained by the circadian rhythmicity which effects the slow variation in HR (VLF) and the impaired performance (VLD) in the late sessions between 05:00 and 07:00 more so than the subjective estimation of sleepiness. The sign of the correlation goes from positive to negative for the frequency regions of the LF and HF bands. The KSS correlates lowly with the LF band (figure 1c) at -0.37, whereas VLD displays a highly significant negative correlation with -0.69 (*). For the PSD of the HF band, significant negative correlations with both KSS (-0.79 (*)) and VLD (-0.69 (*)) are displayed in figure 1d.

An overview of individual correlations for the 0.02-Hz frequency bands with VLD and KSS values is presented above in figures 2a-e. The inter-individual differences between subjects are substantial. Three out of five subjects show significant correlations in the VLF range with VLD and/or KSS. Correlations between frequency bands in the LF range and KSS are varying, the same applies to VLD; only subject 1 shows significant negative correlations with KSS and VLD around the 0.1-Hz component. Significant negative correlations are found as well in the upper ranges of HF bands with KSS for subjects 4 and 5.

Figure 3 correlates the averaged HRV bands of all subjects with the averaged KSS and VLD data. Three strong significant correlation groups appear: (1) VLF range: the 0.01-Hz band from the correlates with VLD and the 0.03-Hz band with KSS; (2) LF range: the 0.11-Hz and the 0.13-Hz band correlate with KSS; (3) LF range: the bands from 0.28-0.32 Hz correlate with KSS, and the 0.29-Hz band correlates with VLD.

## CONCLUSIONS

**Can frequency domain heart rate measures detect impaired driver performance?** The answer is ‘yes’, some can, but there are differences in the sensitivity. These differences can be identified by the analysis of small frequency bands of 0.02 Hz width inside the conventional VLF, LF and HF bands. According to our study, **the best option to detect driver performance impairment is the VLF band**. The relative PSD of the VLF band shows a strong positive correlation to driver performance (VLD) and driver fatigue state (KSS). This is not surprising because the PSD of the VLF band reflects the human thermoregulation (Cerutti et al. 1995). Both KSS and VLD are following the course of the core body temperature, showing a typical time-of-day effect. The detailed analysis of single small frequency bands shows a more distinct picture. The lowest bands (0-0.02 Hz) in general correlate well with driving performance (VLD), and the second lowest band (0.02-0.04 Hz) well with driver fatigue state (KSS).

For the relative PSD of the LF and HF band, the correlations to VLD and KSS are negative. The relative PSD of the LF band correlates only with VLD on a significant level and not with KSS. This situation changes for correlations in the HF band. Here the correlation to the KSS is stronger than the correlation to the VLD. Both correlations are significant. A systematic picture of positive (VLF) and negative correlations (LF, HF) with driver performance (VLD) and driver fatigue state (KSS) could be established from a group of five subjects despite their inter-individual differences.

Our analyses confirm the results discussed in Brookhuis & De Waard (2001) in principle, as the 0.1-Hz component is insensitive to the driver sleepiness state. We found the insensitive frequency range regarding driver fatigue state is not around 0.1 Hz, but below. To be more precise, the insensitive range is between 0.04 Hz and 0.1 Hz. On the other hand, this range between 0.04 Hz and 0.1 Hz, as well as the total LF band, shows a strong correlation to the driver performance (VLD). We conclude that the discussed region should be especially sensitive to the stepwise increase in mental task load by the n-back memory task used by Mehler et al. (2011). In addition, it could help to separate the compensatory component from the computational component of the driver performance.

The systematic characteristics between the introduced fine-grained frequency bands and driving performance, as well as driver fatigue state, **suggest the possibility of predicting driver impairment solely from recordings of heart rate**. Future analysis will show if these results will hold true for larger study populations.

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