The Relevance of HRV Parameters for Driver Workload Detection in Real World Driving

Benjamin Eilebrecht[1], Stefan Wolter[2], Jeroen Lem[2], Hans-Joachim Lindner[2], Rainer Vogt[2], Marian Walter[1], Steffen Leonhardt[1]

[1] Philips Chair of Medical Information Technology, RWTH Aachen, Aachen, Germany
[2] Ford Research Center, Aachen, Germany

Abstract

The automotive industry in Germany is one of the strongest industries, continuously introducing new features for making the driver's life safer and more comfortable. For a couple of years, a trend towards safety systems, considering the driver's status, is observable. Already on the market, e.g. eye motion recognition for fatigue detection will be extended by consideration of additional vital signs. Many research groups already faced the question, which vital signs could be of interest, whereas others concentrated on the realizability of vital sign detection without constricting the driver. One of the most important vital signs, the electrocardiogram (ECG), allows extracting the heart rate variability (HRV), which is known to be affected by mental stress and workload. Latest results of different research groups have shown that an ECG recording in a car is feasible without attaching adhesive electrodes thus making this vital sign potentially available for the next generation advanced driver assistance systems. This paper gives attention to the question which HRV parameters are of interest for driver's workload detection by presenting results of a real world driving study.

1. Introduction

The automotive industry is one of the most competitive industries in the world, constantly forcing the development of new features. Currently many research groups have raised their interest for advanced driver assistance systems such as emergency stop or lane assisting systems. Most of these systems react on the driver's behavior. Therefore sensors gathering relevant information from the driver are installed into the interior of the vehicle. This way, e.g. cameras recognizing the eye movement of the driver and thus detecting driver's fatigue are already available on the market. However, the research interests are broader and there are more parameters and vital signs that allow drawing conclusions about the health or workload status of the driver. Up to now most vital signs are not reliably and comfortably measurable yet in an automotive environment [2]. One of these vital signs is the ECG, which allows extracting the heart rate and its variability (HRV). The HRV was already subject to many studies [1], among which also its validity as a workload or stress index was addressed. Even guidelines for the measurement and interpretation of HRV parameters have already been published [11]. Also the interest of the automobile industry to measure the ECG and use it for safety or wellness features was raised and different research projects were initiated [3][4][5][6]. When extracting the HRV from heart rate time series, a continuous and reliable measurement of consecutive heart beats for at least 5 minutes is required. Kim et al. [9][10] have shown how sensitive the HRV reacts in presence of missing data or misdetections of heart beats. Recently, Eilebrecht et al. [7] as well as Wartzek et al. [8] have shown that a reliable and unobtrusive detection of the heart rate by means of contactless ECG in different driving situations is possible and - certainly on the highway - a reliable ECG is recognizable. However, examinations of the meaning of HRV during real world driving and the driver's workload are limited [2]. This paper deals with the analysis of HRV parameters during real world driving situations, aiming at finding out the most promising HRV parameters for workload measurement in vehicles.

2. Methods and materials

In order to analyze the meaning of the HRV for a detection of a driver's workload a study with four subjects was performed driving from Aachen to Brussels and back to Aachen. In order to cover more and less demanding phases during the drive, both calm highway drives and demanding drives in the city of Brussels were covered by all subjects. Before starting the trip, a medically approved ECG device (Philips M3046A, Philips Healthcare, Hamburg, Germany) was configured according to Einthoven lead I with a sampling frequency of 1 kHz. Since the system had to be operated in battery mode and an uncertainty about the charge state of the battery during the first drive, the recording of the ECG started just at the town entrance and ended back in Aachen for the first driver. For the remaining three drivers all phases, the highway drive to Brussels, the city drive in Brussels and the highway drive back to Aachen were recorded. For workload reference a reduced NASA TLX questionnaire [13] was used, asking for the mental strain of the driver on a scale from 1 to 10. The first driver was asked for his mental strain level every five minutes all over the whole drive. Since this high response frequency was noticed to probably increase the workload of the driver, the frequency of feedback questions was limited to each 10 minutes for the following three drivers.

2.1. Signal analysis

The R-peaks of the ECG signals were extracted by means of an open source QRS detector [12]. The RR-intervals were calculated from consecutive R-peaks and misdetections were corrected manually. Based on the resulting RR time series the following HRV parameters were calculated on a short time basis of 5 minutes. Both time and frequency domain methods were used, where the frequency domain methods were again divided into parametric and non-parametric methods. As a non-parametric method the power density spectrum was calculated by means of a fast Fourier transform (index: FFT), whereas as a parametric method the power density spectrum was estimated by means of an AR model (index: AR). The frequency range used for low and high frequency power were 0.04 Hz – 0.15 Hz and 0.15 Hz - 0.4 Hz respectively:

Frequency domain:

- Low and high frequency power from the FFT spectrum (LF_{FFT} [ms²] and HF_{FFT} [ms²])
- Low and high frequency power from the parameterized FFT spectrum (LF_{AR} [ms²] and HF_{AR} [ms²])
- Percentage of low and high frequency power in the FFT spectrum (LF_{FFT} [%] and HF_{FFT} [%])
- Percentage of low and high frequency power in the parameterized FFT spectrum (LF_{AR} [%] and HF_{AR} [%])

Time domain:

- Mean RR duration (Mean RR [s])
- Standard deviation of the heart rate (Std RR [ms])
- Mean heart rate (Mean HR [bpm])
- Square root of the mean squared differences of successive RR intervals (RMSSD [ms])
- Standard deviation of the RR interval (SDNN [ms])
- NN50 (Number of pairs of adjacent NN intervals differing by more than 50 ms in the entire recording) count divided by the total number of all NN intervals (pNN50 [%])

The HRV parameters were calculated on the average of the same 5 or 10 minutes, which cover the subjective impression of the driver's workload as requested by the workload rating scale. To test the hypothesis that a city drive in Brussels implies a higher workload, at first a comparison of the mean values of the highway drive to Brussels and the city drive in Brussels as well as between the city drive and the highway drive back from Brussels to Aachen was done (analysis A). The division into two comparisons was done to see both changes from low to high and from high to low workload separately. In a second step the mean parameters over the track sections, which were rated by the reduced NASA TLX questionnaire, were correlated with the results of the questionnaire (analysis B).

3. Results

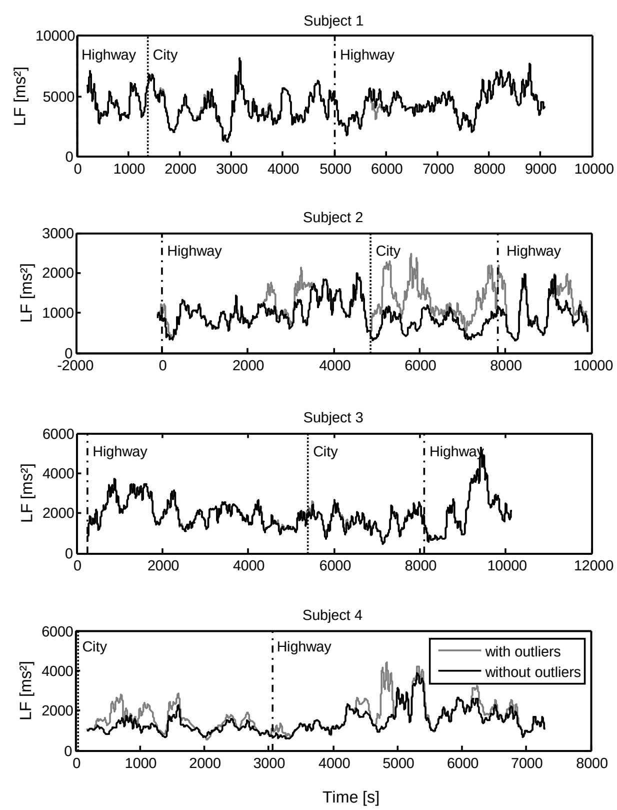

Fig. 1. Behaviour of LF [ms²] during real world driving.

In the real world driving study, 2 male and 2 female subjects were involved (average age of 29.5+-2.08 years). Fig. 1 shows the results of the real world driving tasks for each subject using the example of LF_{FFT} [ms²]. The plots show the continuous time series of LF_{FFT} [ms²] once extracted from the RR-series without the manually corrected RR-intervals (grey line) and once including them (black line). Additionally the onsets of the highway and the city drives are marked by a vertical dash-dotted and dotted line respectively.

Analysis A:

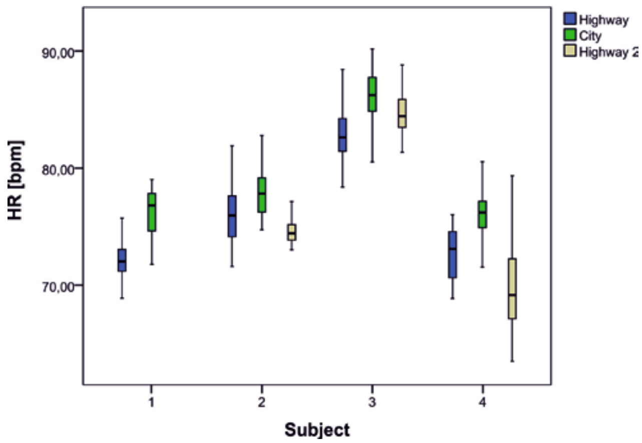

Fig. 2. Boxplot of heart rate for different driving situation and subjects.

Fig. 2 shows the boxplot of the heart rate, plotted for all subjects against the three driving situations (city and highway drives to and from Brussels). As already mentioned above for driver 1 only one highway section was recorded. Before comparing the mean values for both highway drives and the city drives all HRV parameters for each test person were again subject to a test for normal distribution (level of significance: $p<0.05$). As a result of the Kolmogorov-Smirnov-Test none of the parameters can be assumed to be normally distributed. However, the parameters were tested for significance (level of significance: $p<0.05$) by means of the Mann-Whitney-U-test. First, the first highway drive was compared with the city drive leading to a significant deviation in all parameters except for the standard deviation of the RR intervals (Std RR). Second, the second highway drive was compared with the city drive indicating that all parameters differ significantly. However, several parameters (HF_{FFT} [ms²], HF_{AR} [ms²], HF_{FFT} [%], LF_{AR} [%], Std HR [bpm], RMSSD [ms], SDNN [ms] and pNN50 [%]) were excluded since the mean values of the highway drives were once above and once below the values of the city drive.

Analysis B:

In order to identify the meaning of the HRV parameters as workload identifiers, they were correlated with the reduced NASA TLX questionnaire measures.

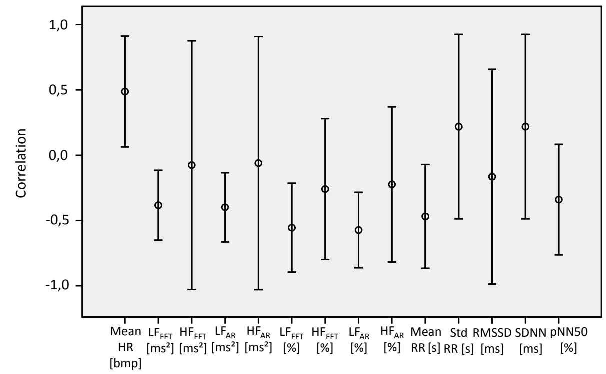

Fig. 3. Error plot of correlations between HRV parameters and driver's subjective workload.

The error plot in Fig. 3 shows the correlations between the driver's subjective workload and the different HRV parameters. The heart rate shows one of the highest correlations with the subjective workload. However, the highest (negative) correlation was achieved by LF_{AR} [%], even with a narrower error band than the mean heart rate. Even though the results should not be overrated due to the limited amount of test persons, slight trends are extractable from the results. As potential workload indicators the HRV parameters, whose average correlation is higher than 0.5 or below -0.5, namely LF_{FFT} [%] and LF_{AR} [%], were identified.

4. Discussion

Even though the limited amount of subjects reduced the power of significance, the results indicate, which parameters should be subject to a bigger trial. A drawback of the analyses presented in this paper is the fact that the reference, the reduced NASA TLX questionnaire, is a subjective measure. It is unclear if the subjective feeling of a driver corresponds to the real workload he is exposed to. Certain driving situations may affect the driver's attention more than perceived. An alternative approach for assessing the driver's workload would be to quantify the remaining cognitive capacitance, which is not used for the driving situation. This could e.g. be done by exposing the driver to additional tasks, he has to solve. However, this could lead to critical incidents and should not be applied in real driving situations but be considered for measurements in car simulators. As this study aimed to access the reaction of drivers in real world driving situations the reduced NASA TLX questionnaire appeared to be the most reliable tool.

5. Conclusion and outlook

The results in this paper presented indicate, that some HRV parameters are more reliable for a workload detection of drivers than others. However, on the way to reliable workload detection and new advanced driver assistance features based on online HRV analysis, several obstacles have to be overcome. Beginning with the signal recognition, a reliable ECG without too many artifacts needs to be recorded continuously. With the recent developments in ECG sensing [7][8], at least a continuous recording seems to be realizable, even though the accuracy of the R-peak detection will also in future be subject to research. Even if research groups report on detection rates of about 95% [7], this rate still needs to be increased and reliable motion artifact detection to be implemented. Solving these issues, the relevance of the choice of frequency thresholds for discriminating the heart rate spectrum needs to be addressed since it can be assumed that the distribution of the spectral power is individually different. Even though the spectrum of the heart rate can not directly be compared with the mean heart rate, one can imagine that there are severe differences in the spectrum of athletes and obese people as it is the case for the resting heart rate. Thus, an individual variation of the frequency bandwidths (LF, HF) would potentially increase the significance of HRV parameters in the frequency domain, though accompanied by a reduction in the comparability with other studies. Nevertheless, broader studies need to be carried out in order to increase the statistical significances reported in this paper. Furthermore, the time dependence of HRV parameters is not completely understood yet. Although the parameters are considered to instantaneously react to external influences, particularly stress is not an instantaneous impulse rather than a creeping process and thus slower physiological mechanisms also should be considered, as they may cause a delayed response of the HRV parameters. However, the spectrum of influences on the heart rate variability is broad and the heart rate itself seems to be a good workload indicator, although it is also known to be affected by many other influencing factors. This suggests that the HRV in future will not be the only parameter to be used for workload detection, but more physiological measures, such as skin conductivity, gripping pressure on the steering wheel, respiration or blood pressure should be considered. Then it could be feasible to define workload indices leading to more reliable measures which could potentially be helpful for automotive safety features or human-machine interfaces adapted to driver's state.

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Dipl.-Ing. Benjamin Eilebrecht
Chair of Medical Information Technology
RWTH Aachen University
Pauwelsstraße 20
52074 Aachen
Germany
eilebrecht@hia.rwth-aachen.de