A Mobile Sensing Approach to Stress Detection and Memory Activation for Public Bus Drivers

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***Abstract*—The experience of daily stress among bus drivers has shown to affect physical and psychological health, and can impact driving behavior and overall road safety. Although previous research consistently supports these findings, little attention has been dedicated to the design of a stress detection method able to synchronize physiological and psychological stress responses of public bus drivers in their day-to-day routine work. To overcome this limitation, we propose a mobile sensing approach to detect georeferenced stress responses and facilitate memory recall of the stressful situations. Data were collected among public bus drivers in the city of Porto, Portugal (145 h, 36 bus drivers, +2300 km), and results supported the validation of our approach among this population and allowed us to determine specific stressor categories within certain areas of the city. Furthermore, data collected throughout the city allowed us to produce a citywide "stress map" that can be used for spotting areas in need of local authority intervention. The enriching findings suggest that our system can be a promising tool to support applied occupational health interventions for public bus drivers and guide authorities' interventions to improve these aspects in "future" cities.**

***Index Terms*—Public transportation, driver, stress detection, wearable technologies, georeferenced data analysis.**

I. INTRODUCTION

DRIVER behavior constitutes a major concern in road safety research and policy. Since buses are one of the most used modes of public transportation worldwide, the behavior of bus drivers and their occupational health becomes a critical priority in overall road safety [1].

Epidemiological evidence from several studies conducted mainly in North America and in Western Europe showed that urban bus drivers have substantially higher mortality rates and higher risk to develop physical and psychological diseases in comparison to many other occupational groups [2]. In agreement with this findings, a meta-analysis by Tse *et al.* [1] reviewing fifty years of research in the area of bus driver well-being concluded that this population is exposed to several sources of stress over time. These can be distinguished in three main categories: physical environment, job design and organizational issues. Physical environment includes sources of stress related with cabin ergonomics, exposure to noise, weather conditions, threat of physical violence, and traffic congestion aspects. Job design includes responsibility for security and schedule obedience, working in shifts, long periods of social isolation, ticket selling and control. Organizational issues are related to bus drivers low autonomy and limited decision-making authority. Finally, bus drivers profession is associated with high sedentarism levels, which is known to be a major cause for cardiovascular diseases [3].

The task of driving involves considerable strain for bus drivers, ranging from the needed awareness to safeguard passengers, to traffic hazards [4]. The diversity of daily demands faced by this population causes detrimental effects to their physical and psychological health and well-being, as supported by studies conducted in the occupational [5], ergonomic [6] and biomedical areas [7]. Furthermore, it can also increase the risk of accidents, decreasing overall road safety [1]. Also, stress caused by emotional upsets has been associated with several incidents among drivers [8]. This is probably explained by the fact that emotional states of anger and frustration can increase driver distraction and impair driving performance [9]. Additionally, bus drivers role is often conceptualized as high in demands (i.e., traffic congestion, rotating shift patterns, negative passenger interaction, tight running times, workload demands, etc.) and low in control with respect to limited decision latitude [6]. This is a main cause for psychological problems [2] and cardiovascular diseases [10].

In agreement with this idea, an investigation by Baevskii *et al.* [7] aiming to study the use of principles of prenosological diagnosis for assessing the functional state of the body, has found that bus drivers experienced chronic occupational stress leading to exhaustion of regulatory mechanisms and to rapid development of cardiovascular pathology. As explained by the authors, long-term mental and psychoemotional tension in bus

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drivers was associated with occupational stress, and leads to the worsening of psychophysiological and cardiorespiratory function of the body. The degree of stress was assessed in this study based on analysis of Heart Rate Variability (HRV).

While there is no definitive method of directly assessing physiological stress levels, many techniques have been identified in the literature, such as heart rate and HRV metrics, electrodermal activity, respiration rate, electromyography and blood volume pressure [11]–[14]. Their results suggest that stress events do indeed cause a reaction perceivable in physiological signals, and that using multiple physiological inputs and incorporating driving event information can greatly increase drivers' stress detection accuracy [15], [16].

Although, one can question the ecological validity and reliability of driver stress measures collected in laboratory conditions [17]. In opposition, stress assessment research among drivers should take place in ecological settings including non-intrusive physiologic stress monitoring. Recent advances in noninvasive measurement techniques allowed the progression of human developmental stress research [18], including ambulatory monitoring of cardiovascular function [19]–[21]. HRV can be calculated from the Electrocardiogram (ECG), and is reported to be an accurate measure of stress [13]. Recent studies were able to correlate stress with some non-linear HRV features [22], while time-domain and frequency-domain features extracted from HRV have been validated multiple times as stress indicators in the last decades [13], [14], [23].

Nevertheless, stress assessment in ecological settings among bus drivers is not always an easy task, mainly due to difficulties faced when aiming to collect their physiologic and psychological stress responses during operation of public vehicles in urban centers [24]. Previous research in this area [25], [26] associated physiologic (e.g., blood pressure levels, pulse, and urine samples) and psychologic (e.g., self-report and/or researchers observation) measures of stress, and data was collected during bus drivers rest periods. Although these studies provided a crucial contribution to the understanding of daily stress among bus drivers, they are plagued by limitations highlighted below. Primarily, physiologic measures used do not include HRV, considered to be one of the most viable physiologic assessments of stress [14], [23]. Secondly, these research designs failed to understand the physiologic and psychologic impact of a specific source of stress on the driver [27]. Thirdly, the retrospective self-report assessments of sources of stress at the end of a working day may be plagued by attention and memory bias, limiting the driver ability to recall acute stressful events [28]. It is well known that the experience of stress affects quality of memory recall [29]. Furthermore, bus drivers deal with numerous tasks and challenges throughout a day at work (e.g., driving, interaction with passengers and other drivers). Hence, previous research has shown significant discrepancies between real-time assessments and retrospective recall [30], questioning how accurate and valid are results that rely merely on bus drivers memory construction and retrieval.

Towards this goal, the current paper proposes an interdisciplinary method that combines physiologic, psychologic and georeferenced data to investigate sources of stress faced by bus drivers while driving in an ecological setting on a daily work basis. Our contribution includes the design of stress assessment software, adapted to the routine needs of bus drivers, and combines non-intrusive, user friendly and reliable physiologic and psychologic research methods, providing a continuous daily monitoring of the driver during the course of a day at work. To overcome previous retrospective self-report assessments among bus drivers, our methodology provides a digital contextualization of potential sources of stress, including environmental cues to trigger memory retrieval [31]. Furthermore, this information is synchronized with the physiologic response for each stressor and the georeferenced location.

Hence, findings will benefit future evaluation of stress sources among bus drivers and will foster the design of efficient occupational health and local road safety interventions.

II. METHODOLOGY

In this section we describe the technology and methodology that was iteratively improved by real-world experiments with professional bus drivers in the city of Porto, Portugal.

A. *Sensing Platform*

Our project targeted a large population, and thus our platform was designed to be very easy to use and have very low intrusiveness. These were critical for the wide acceptance and participation we achieved, with 36 volunteers out of 37 drivers introduced to the project.

1) Physiologic Sensors: One kit of equipment was provided to each bus driver, including a VitalJacket,[1] disposable electrodes, a Global Positioning System (GPS) receiver and a netbook PC. The Vital Jacket (VJ) is a wearable bio-monitoring platform in the form of a t-shirt that provides real time electrocardiogram (ECG) with 500 Hz sampling rate, 3 axis accelerometer and an event push-button [21], [32]. This data is transmitted to the netbook via Bluetooth from a small box embedded in an easily accessible pocket on the t-shirt.

2) Self-Report Measures: Health and demographic questionnaires were completed by participants. This data was used to analyze the impact that demographic metrics have on the drivers' physiologic response (Section IV-C).

Furthermore, bus drivers provided a description of each potential stressor, followed by a stress intensity rating, based on their appraisal of the particular situation. Potential stressful situations were either detected by the system or tagged by the drivers using the push-button incorporated in the VJ. Stress intensity was assessed using a "stress thermometer" where the participant dissected a 10 cm bipolar line anchored by two statements ("not at all stressful" vs. "extremely stressful"). The "stress thermometer" has demonstrated normal distribution properties and adequate variability in previous stress assessment research [33], [34].

3) System Architecture: The GPS receiver used was placed near a bus window and transmits information to the netbook via Bluetooth. A small and lightweight netbook, chosen for its

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[1] BioDevices S.A., www.vitaljacket.com.

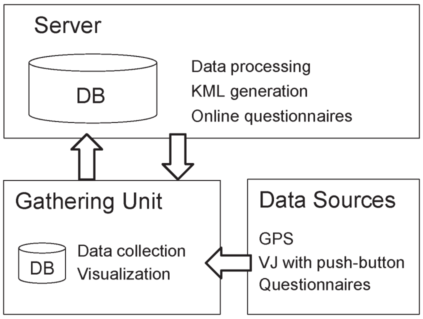

Fig. 1. Hardware architecture.

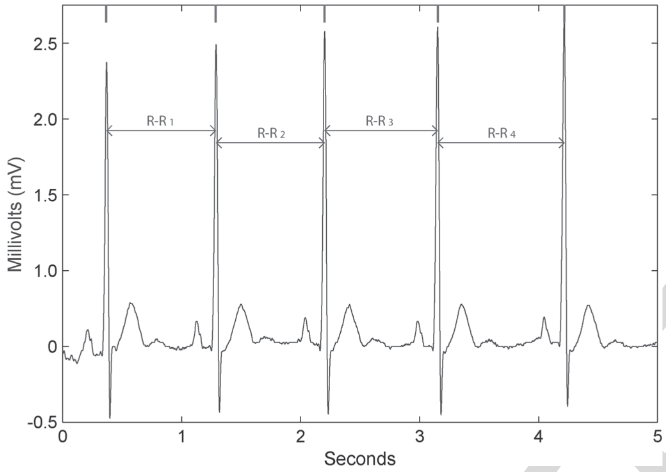

Fig. 2. Sample ECG signal collected from a bus driver and R-R measures.

portability, served as the gathering unit. Data processing was performed on a cloud server to increase processing speed. The netbook was used further for visualization in the recall phase (see Section II-B), and the required Internet connectivity was provided by a 3G network adapter.

The architecture of the system designed and implemented to integrate the previous materials is shown in Fig. 1. This architecture and gathering capabilities, such as sensor-data synchronization, reliability and communications have been tested and validated in previous work [35].

4) Signal Processing Software: The processing of the ECG signal was performed using the open-source library PhysioToolkit from Physionet [36], which follows the recommendations proposed by the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology [13].

We used the GQRS tool from the library to extract heartbeat information from the ECG. Fig. 2 shows a 5 second ECG segment with the R peaks marked at the top. This tool determines the moment of the peaks for each heartbeat and outputs the inter-beat intervals (R-R) in a format compatible with other Physionet tools.

Extra processing and filtering of the cardiac signal was required, as explained in Section III-C, due to the presence of very noisy signals, which can occur in real world research.

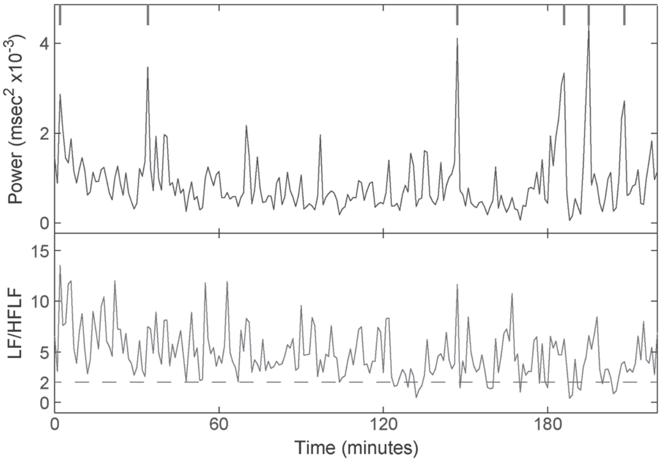

Fig. 3. Low Frequency Power and the ratio between Low Frequency and High Frequency power, for a 3 hour long trip. We use the standardized LF Power to detect stressful events, marked in the top horizontal axis.

We used the HRV Toolkit from Physionet to perform time-domain and frequency-domain analysis of the heart rate information, as suggested by the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology [13]. We performed the analysis using a window size of 100 s with a shift of 60 s between consecutive windows, and the results were stored for further statistical analysis (which we denominate HRV blocks). We decided to use overlapping windows to improve the time accuracy of the results, but we downsample the results when independence between samples is required (see Section III-C). The window size of 100 s was chosen in order to have a 0.02 Hz of frequency resolution in the frequency-domain results without upsampling. Among others, the metrics include the average normal-to-normal (NN) intervals, the standard deviation of these NN intervals, their low frequency spectral power (LF) between 0.04 Hz and 0.15 Hz, the high frequency power (HF) between 0.15 Hz and 0.4 Hz, and the ratio LF/HF.

The spectral power of different frequency bands is specially important to our study, because the power in the HF band is mainly mediated by the parasympathetic system and encompasses respiratory sinus arrhythmia, but the LF band is mediated by both the parasympathetic and sympathetic components, and so they might provide a robust way to assess individual stress [37]. Fig. 3 shows an example of the evolution of the LF power and the LF/HF ratio, which are the two metrics most correlated to stress according to [12] and [23]. The figure shows that spikes are more distinct in the LF than the LF/HF case. A statistical analysis (Section III) confirmed this, leading us to use the LF power as a stress indicator.

5) Detecting Stressful Events: Potentially stressful events were selected from all the moments the driver pushed the button on the VJ, combined with additional 10 blocks with the driver's highest physiologic stress (LF component) but separated at least 5 minutes between each other.

6) Enquiry and Visualization Tools: The processed ECG data, together with the GPS information, was used to generate a map at the end of each driver's shift.

Fig. 4. Visualization of a trip and stress events in Google Earth. The height of the traces represents bus speed, ellipses denotes events.

The map was visualized using Google Earth (Fig. 4), providing a straightforward approach to overlay spatial data and correlate different types of information. Free camera movements and a time toolbar, used to select a time interval window to be displayed, allowed to easily analyze the detected events and their context. To facilitate memory recall, we overlaid information about location and time of the events, as well as the speed of the bus in the whole trip, plotted using a line segment over the map with the height of the line representing speed. By displaying the speed profile for every second of the trip, the driver and researcher could easily identify bus stops and driving events information, such as aggressive braking, accelerations (as in Rigas *et al.* [16]) and others, aiding them recall and characterize the events. In the map, the detected potentially stressful events were displayed as ellipses spanning over the area traveled during the corresponding 100 s HRV block.

The Internet connection from the 3G network adapter was used to access Google Earth and refresh the maps and to synchronize the driver's self-report data to the server. Moreover, the netbook also leveraged this Internet connection to speed up the processing of the ECG signal, sending the raw data to a server that performed all the needed computation and generated the maps. This upload and cloud processing took around 4 minutes for a 6 hour work shift. If the computation had been done locally, it would have taken around 15 minutes for the same workload.

B. Procedure

On the day prior to data collection, participants completed a demographic and health questionnaire, and received a kit containing the required equipment. At this time they were given a detailed explanation of the procedures by a researcher. On the data collection day, the bus driver followed the workflow depicted in Fig. 5, wearing the VitalJacket and turning on the netbook and GPS receiver at the beginning of the work shift. Following this procedure, the bus driver was ready to start his work shift, carrying the kit for a full day. The participant was instructed to press the button on the VitalJacket in case of appraising a potentially stressful event during the day, affecting his or the passengers well-being. At the end of the shift, a researcher met the participant at the station, and ran the cloud processing algorithms over the gathered data. A map was then produced displaying the information for the full workday of that participant, as described in Section II-A6.

For each of the displayed ellipses, the driver visualized the exact location and extra information using Google Earth (Fig. 6). For the cases when the participant could remember the event, he was asked to recall that particular situation, and to provide a brief description followed by the stress intensity evaluation for that particular event. The description of the events and stress intensity evaluation were completed in the netbook, but stored and synchronized with the physiologic data on the cloud server.

The protocol was designed to obtain the following independent data sets to help in the detection and categorization of the events:

- Tagged events, providing annotations of on-site self-reported stressors including a description of the situation experienced and stress intensity evaluation;
- Physiologic responses measured with biomedical sensors—HRV blocks;
- Location and velocity information assessed from GPS data, used to detect driving events and facilitate memory retrieval.
- Short annotations for every stressful event detected by the system and confirmed by the driver as stressful, including a description of the situation experienced and stress intensity evaluation.

This method provided an accurate connection between the georeferenced data, description of the stressor experienced and stress appraisal evaluation for a particular stressor, synchronized with physiologic and driving response data. The ellipses provided a general vicinity to the memory retrieval of the event, contextualizing time and location information. Additionally, the method allowed the driver to isolate certain events during the working day by pushing the button. These were saved in the system and available for description and stress intensity evaluation later at the end of the work shift.

III. DATA ANALYSIS

A. Samples and Population

Thirty-six male professional bus drivers, aged between 29 and 55 years old (Mean = 41; Standard Deviation = 6.5) with experience in bus driving between 3 and 25 years (M = 13; SD = 6.0), participated in this study. All participants worked for the major transportation company in the city of Porto, Portugal. The exclusion criteria for the study were participants having a history of cardiovascular disease and/or taking prescription drugs known to affect cardiovascular function. Participants volunteering to participate in the study were instructed to perform no changes in their daily routine, such as sport activities and caffeine, nicotine and food consumption.

Following approval of the study by the bus company administration, bus drivers were invited to participate. For this purpose a presentation session was organized by researchers, explaining the aim and protocol of the study. Participants provided informed consent forms prior to participation.

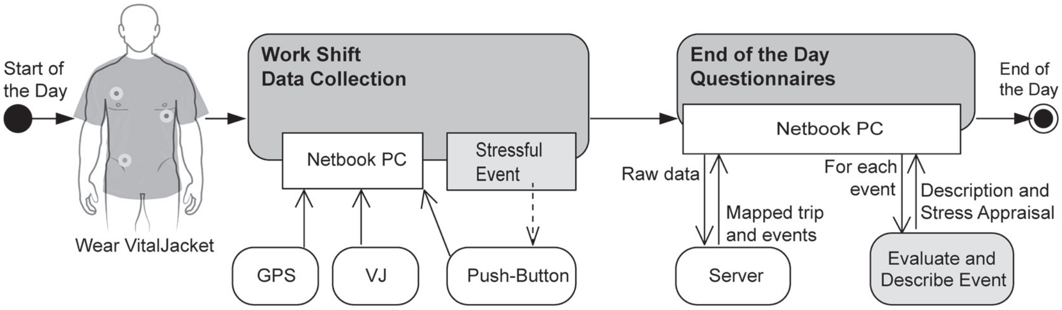

Fig. 5. Workflow on daily data collection.

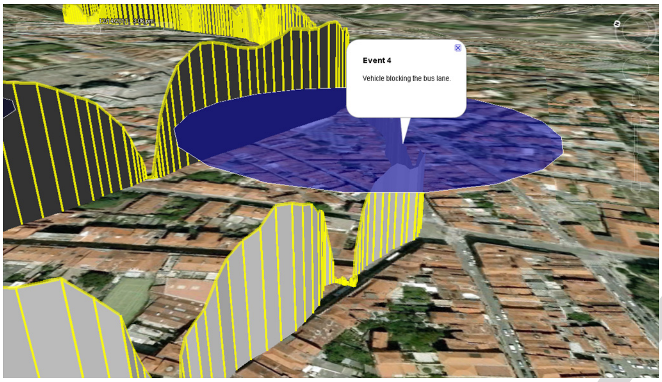

Fig. 6. Close-up of a stress event in Google Earth. The height of the traces represents bus speed.

Data was collected for each bus driver over a full working day, corresponding to approximately 5 hours of driving, divided in one or two daytime shifts occurring between 8 AM and 8 PM. In total, this study gathered 151 hours of data, including 500 Hz ECG and location information stored every second that spanned more than 2.500 kms.

B. Stressor Categories

Each situation of stress described by the drivers in the 86 events was subjected to a content analysis to identify stressors categories. The identified categories are similar to a great extent to the job hassles reported by previous research [27], with a few exceptions discussed in Section V.

The first two authors then independently assigned each event into 5 major stressor categories or event types.

1) Social interactions (e.g., with passengers or friends);
2) Unexpected situations (e.g., mechanical failures, driving mistakes, unexpected changes);
3) Other drivers or pedestrians behaviors (e.g., other drivers risky behaviors and lack of politeness);
4) Events that impact time schedule (e.g., traffic congestion);
5) Difficult driving due to urban planning (e.g., narrow roads and tight corners).

A reliability check showed a level of agreement of 98.8% between both researchers after the first categorization. Following some discussion, this agreement increased to 100%.

C. Filtering and Processing the Physiologic Data

1) Synchronizing the VJ and GPS Clock: The Physionet library can process the cardiac signal and outputs the metrics we need. However, some extra steps were required in order to synchronize the Physionet output with our GPS data.

We used the GQRS tool from Physionet to detect heart beats, which takes the ECG signal as input with a specified starting time and sample frequency, and outputs the timestamps of every detected beat. Even though the VitalJacket, our ECG sensor, has a fixed 500 Hz sampling rate, small errors in the VJ clock precision and in the Bluetooth communication can cause discrepancies between the timestamps and duration of the ECG and the GPS data. This clock drift is negligible at the beginning of a trip, since a starting timestamp is given to the application, but naturally increases as the time passes, and sometimes resulted in errors of more than 15 minutes at the end of the 6 h trips in our pilot experiments. A small desynchronization between the VJ and GPS clocks can cause a huge misplacement of a stressful event, since buses can travel at up to 50 km/h (14 m/s)

To correct this synchronization issue our processing algorithm keeps track of the GPS clock and also of a virtual one that follows the beat-detector fixed 1/500 s per data sample. The differences between both clocks is constantly analyzed, and the ECG stream is split and given a new corrected timestamp every time a shift of more than 10 s is detected.

2) Detecting Noisy ECG Data: Another problem we detected in our pilot experiments when processing the data was ECG noise. The heartbeat detectors perform poorly in the presence of very noisy signals that can occur in real world scenarios like ours, leading to the detection of false-positive stressful events. There are many sources of noise in a real world environment, such as from other muscular activity or electrode misplacement, which can significantly reduce the accuracy of the heartbeat detection algorithms.

We implemented a Standard Deviation (SD) filter to detect extremely noisy blocks of data and improve the reliability of the ECG data. This filter calculates the SD of the raw ECG every second (500 samples), discarding an HRV block from the analysis if it contains any second with an SD higher than a threshold. The filter successfully detected the trips belonging to 2 drivers who misplaced the electrode patches, and also other 3 trips that presented problems with the electrodes' connection after some point in the middle of the trip. After analyzing these trips, the threshold was set as the 90th percentile of all of our data, eliminating the 10% noisiest ECG data gathered in our real world scenario. The SD filter was applied to 151 h of gathered data, resulting in 1470 discarded HRV blocks. From these, 1349 (92%) belonged to 5 trip segments with problems in the electrode patches.

3) Push-Button Time Correction: Another filtering step was the correction of tagged events' timestamps. This consisted in correlating the push-button events with the correct HRV block of physiologic sensor data by analyzing the driver description of the event and surrounding trip data, such as location and speed. Most of the events were associated with the block that immediately preceded it, meaning that the drivers pressed the button right after they experienced a stressful situation. However, in some cases they were associated with the following block, because some drivers pressed the button when approaching a known dangerous place.

4) HRV Metrics Standardization: Different drivers have different cardiac characteristics and baselines, preventing us from comparing HRV metrics between multiple drivers. Since we could not collect a baseline for each driver in a relaxed and controlled environment, we decided to standardized the cardiac metrics per driver. To this end, the HRV metrics of each driver's entire collection day were transformed to have zero mean and unit variance.

5) Downsampling to Independence: The final step in our processing algorithm was the downsampling of the HRV blocks for each driver in order to increase independence between samples. The recalled events were already selected with at least 5 min of data between them. However, the rest of the ECG was analyzed every minute but with a window size of 100 s, resulting in 40 s overlap between HRV blocks, and producing a dependent dataset of HRV metrics. To make the HRV blocks independent, the processed and filtered blocks were downsampled for each driver, removing the minimum number of blocks that guarantees the same 5 min distance between HRV blocks or any recalled or tagged events.

IV. RESULTS

We gathered a total of 9081 HRV Blocks, from which 1470 were filtered as noise and 6050 were removed in the downsampling process. From the 36 drivers, 2 had misplaced electrodes providing no useful ECG data and other 2 forgot to turn on the GPS device. 29 events were tagged on-site as stressful by 11 drivers. Some drivers forgot they were being monitored and thus forgot to press the button in stressful situations, others were distracted dealing with the situations.

To facilitate the events recall, 320 distinct blocks were identified by the system and shown to the 32 drivers in the map at the end of the day. From these, 57 blocks were recalled as stressful events and evaluated by 27 bus drivers, 2 drivers did not recall any additional events besides the ones they tagged, and 3 stated they did not experience any stressful situations during their work shift.

Our final dataset to be analyzed contains stress information from 29 drivers, with 29 on-site tagged events, 57 events recalled at the end of the day, and other 1475 HRV blocks not identified as stressful. Thus, a total of 1561 independent rows of data standardized per driver.

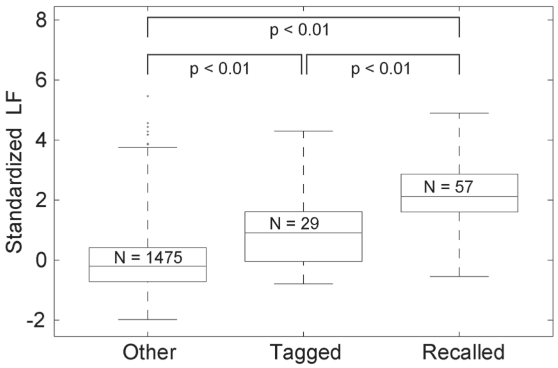

Fig. 7. Distribution of calculated stress between other blocks, tagged events, and events recalled at the end of the day.

Due to non-normalized distributions of the data, we used non-parametric tests. The Mann-Whitney U-Test [38] was chosen to compare the distributions of two populations, the Kruskal-Wallis Test [39] to verify if more than two populations have the same distributions, and the Kendall's Tau [40] to check for statistical dependence between variables in the same population. To this end, multiple pairwise MannWhitney U-Tests were conducted to analyze differences in the main HRV metrics between the samples classified as tagged events, recalled events and others. Kruskal-Wallis Test was conducted to test for differences in the LF spectral power across stressor categories in both self-reported and cardiac stress responses. Kendall's Tau rank correlation test was used to search for statistical association between demographic and physiologic variables.

A. Physiologic vs Recalled Stress Assessment

Our system used the LF component of the interbeat intervals as a stress indicator, as proposed by [12] and [23]. To validate this proposition, we compared the LF frequency component of all blocks, the tagged events and the stress events recalled at the end of the day (Fig. 7).

The MannWhitney U-Test showed significant difference between the distributions of LF power for other and tagged events $(z = -4.91, p = 9.16^{-7})$, indicating that there is a significant increase of the LF power during events appraised as stressful by the driver. The recalled events also presented a statistically higher LF component than the tagged events $(z = -4.85, p = 1.23^{-6})$, even when analyzing only the 11 drivers who tagged events.

The same statistical analysis between tagged and other events was performed for every HRV metric, and some are presented in Table I. The metric that showed the most statistically significant difference was the LF power, followed by the time-domain metrics that detect variability, such as standard deviation of heart beat intervals.

TABLE I
DISTRIBUTION TESTS' RESULTS BETWEEN OTHER AND TAGGED EVENTS OF DIFFERENT HRV METRICS FROM THE HRV TOOLKIT

MannWhitney	AVNN	SDNN	pNN50	LF	HF	LF/HF
Z value	-0.68	-4.19	-2.75	-4.91	-2.39	-1.42
P value	0.50	< **0.01**	< **0.01**	< **0.01**	**0.02**	0.16

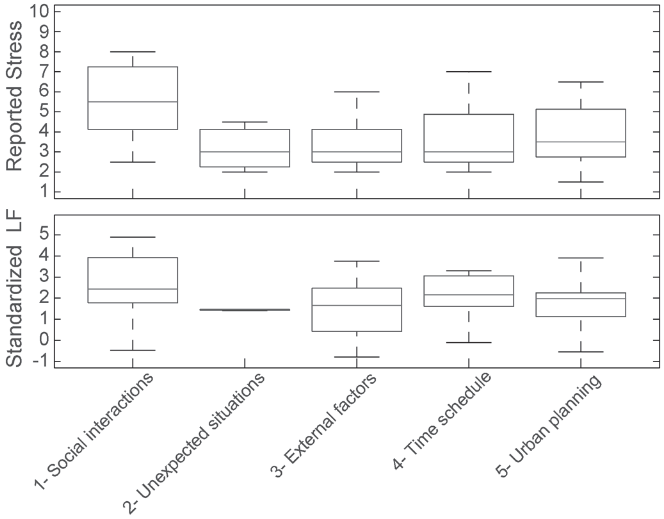

Fig. 8. Distribution of the stress level throughout the different stress categories, for both reported stress evaluated by the stress thermometer, and calculated from the ECG signal.

TABLE II
FREQUENCY ANALYSIS FOR REPORTED STRESSOR CATEGORIES: NUMBER OF REPORTS, FREQUENCY RELATIVE TO THE TOTAL NUMBER OF EVENTS, NUMBER OF DISTINCT DRIVERS THAT REPORTED THAT CATEGORY, AND CORRESPONDING RELATIVE FREQUENCY TO THE NUMBER OF DRIVERS

Stressor Category	1	2	3	4	5	Total
Total Count	14	7	30	16	19	86
Relative Frequency	16%	8%	35%	19%	22%	
Drivers	11	6	18	12	12	29
Drivers Frequency	38%	21%	62%	41%	41%	

B. Analysis of Stressor Categories

Fig. 8 shows an overview of the distributions for physiologic and self-reported stress intensity evaluation for each stressor category, introduced in Section III-B. An event was only considered to be stressful when appraised by the bus driver as higher than 0 in the stress thermometer scale (51 of the 86 identified events).

The Kruskal-Wallis Test showed that no significant differences across stressor categories exist either for self-reported $X^2(4, N = 51) = 7.62; p = 0.11;$ or for cardiac stress responses $X^2(4, N = 51) = 4.82; p = 0.31$.

Table II shows a frequency analysis of stress categories combining all tagged and recalled events appraised as stressful by bus drivers. Other drivers or pedestrians behaviors were the most commonly reported source of stress, reported for 35% of the recalled or tagged events and mentioned at least once by 62% of the 29 bus drivers. Difficulty driving due to urban planning was the second most reported source of stress, reported for 22% of the events recalled or tagged, and mentioned by 41% of the drivers (12/29). Also, events that impact time schedule was a frequently reported source of stress, accounting for 19% of the events and mentioned by 41% of the drivers.

TABLE III
KENDALL'S TAU TEST RESULTS FOR DEMOGRAPHIC AND FULL-DAY CARDIAC METRICS. P VALUES LOWER THAN 0.05 ARE MARKED AS BOOLEAN

	Age		Weight		Experience	
	Tau	P	Tau	P	Tau	P
AvgAVNN	0.0	0.84	0.3	0.06	-0.3	**0.02**
AvgSDNN	0.0	0.87	0.1	0.72	-0.3	**0.01**
AvgLF	-0.1	0.32	0.1	0.63	-0.3	**0.04**
AvgHF	-0.2	0.09	0.1	0.45	-0.3	**0.02**
AvgLF/HF	0.1	0.37	-0.1	0.72	0.0	0.93

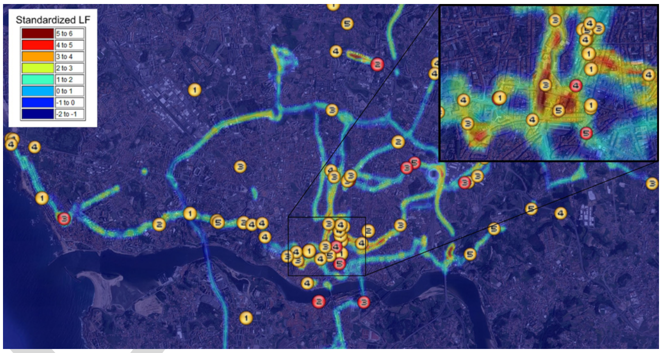

Fig. 9. Stress map of Porto with placemarks on detected stressful events. The numbers represent the event category, the darker marks are tagged events and lighter are events recalled at the end of the day.

C. Questionnaires and per Driver Analysis

In this project we also analyzed the questionnaires data and their correlations with the cardiac metrics. We combined the questionnaires answers with the HRV analysis over each driver's full dataset, resulting in metrics such as a driver's age, height, weight, years of experience as a bus driver, usual exercise routine, and also the full day's average heart rate, average spectral power for different frequencies, and others.

To analyze the data we performed cross-correlation analysis between all variables using Kendall's Tau (τ) rank correlation test [40]. The main results are presented in Table III, with correlated variables resulting in a p-value lower than 0.05 marked in bold.

The results show a strong correlation between the cardiac metrics and the years of experience of the drivers, and not with any other demographic metric.

D. Geo-Referenced Stress Analysis

Furthermore, the analysis of the tagged and recalled stress events showed that more than 75% (65/86) of the stressors are location-dependent, such as tight roads, low-visibility crosswalks and drivers not respecting signalization on some crossroads. This data suggests that the geographic reference of detected events provided by our method was efficient in facilitating bus drivers' memory retrieval, and also that it is possible to provide valuable stress-maps to decision makers. With both physiologic and psychologic stress assessment performed with our methodology, we are able to map their intensity and detect systematically stressful locations.

Fig. 9 shows a stress map of the city of Porto, where lighter areas represents less stressful and darker areas represents highly stressful places. Also, darker symbols mark the spots where stressful events were tagged, lighter ones were recalled at the end of the day, and the numbers correspond to the event category as stated in Section III-B. The map was generated by clustering and averaging the Standardized LF information of the HRV blocks. Additionally, in order to eliminate biases in the cardiac data associated with physical activity, we discarded data gathered while the bus was almost stopped (less than 5 km/h) and only map clusters with data from at least 3 distinct drivers.

Based on Fig. 9 it is clear that the city downtown, near the center of the map, is a stressful region with many highly-stressful roads being detected in that dense urban zone. However we can also find other less obvious highly-stressful zones, such as in the left-middle edge of the map, where a roundabout caused a cardiac response in all of the 4 drivers that passed by and even a tagged event from one of the drivers.

V. DISCUSSION

The aim of the current paper was to investigate daily sources of stress faced by bus drivers while driving in an ecological setting during their daily work. Results suggest that the proposed method is accurate in detecting psychological and physiological stress responses. Despite the divergence in the concept definition and assessment of stress, our findings are consistent with previous research recommendations [41].

Particularly, results showed a significant increase of the LF component of HRV during events appraised as stressful by the driver, suggesting that the stress concept assessment can combine both psychologic and physiologic dimensions of stress, while also contemplating an integrative approach in the real world. Contrary to the results presented by McCraty *et al.* [12] and Healey and Picard [23], the LF/HF does not show a statistically different distribution between tagged stressful events and other HRV blocks, which may be due to the higher HF noise present in real word scenarios like the one in this study. This indicates that the LF power is the best stress metric for our scenario.

Regarding demographic factors and their impact on the drivers' physiologic response, results indicate that years of experience of the driver is an important factor to consider. Surprisingly, even the age, which is correlated with the years of experience, is not significantly correlated with the physiologic metrics. This suggests that, although cardiac response is known to decrease with age [42], more experienced drivers (not necessarily older ones) have less cardiac response to stressful events and a smoother physiologic response throughout the entire working day. Further research is required controlling for bus drivers routes in order to confirm whether this finding is due to effective coping strategies developed by this population or the experience of different environmental demands.

In what concerns to sources of stress found in our study (Section III-B), these are similar to a great extent to the job hassles reported by Johansson *et al.* [27] among bus drivers working in the city of Stockholm (e.g., traffic congestion, illegal parking of vehicles, risky or impolite behaviors of other divers or pedestrians, mechanical difficulties, timetable restrictions). However, in the current study, social interactions with passengers or friends and bus driving mistakes were also reported as stressors in 16% of the reported events and by 38% of the drivers (11/29). We believed that this fact may be mainly related to the methods used in this study that facilitated the drivers memory retrieval of events. On the other hand, previous research methods used across studies relied on retrospective self-reports following long periods of time what may had affected the type of stressors reported. Additionally, other previous studies were based on the researcher observations, whereas our study relied on a more ecological setup and based on the inputs of the drivers themselves, i.e. their own perceptions and experiences of stress. As a result, stress categories such as the experiences of interpersonal stressors are unlikely to be reported by others, who merely described what they can observe. Also, the constant presence of an observer may produce biased results, making the driver less likely to do driving mistakes and avoid communicating with friends entering the bus. Hence, we believe that the type of stress categories found in this study complements the literature in the area and reinforce the strengths of the methodology used to capture drivers acute stressors experienced on a daily basis.

It is important to highlight that the current ecological method culminates a previous limitation in the area of stress reactivity assessment [43], and provides a crucial contribution to the study of cardiovascular reactivity to stress in real world scenarios. This is a fundamental relationship when investigating sources of stress, critical to the etiology of cardiovascular disease [27]. Furthermore, as suggested by Myin-Germeys *et al.* [44] stress responses assessed in real life situations are more likely to be closer to reality than those collected under laboratory settings.

Additionally, the inclusion of georeferenced information and its visualization by bus drivers was a key aspect in this methodology, facilitating memory retrieval of the experienced situations, thus providing a detailed description and specificity of stressors. To support this argument the proposed methodology allowed the collection of 57 additional stressors in the city of Porto, compared with only 29 voluntarily tagged by bus drivers.

In sum, the proposed methodology provides detailed information of different stressors experienced by bus drivers, and their specific location in a city. It is believed that this information can induce evidence based decisions across a variety of areas (e.g., ergonomics, security, management, technological, public policy, psychologic and urban planning). Additionally, the system is able to map exactly where in the city these events have occurred and the average stress intensity for the sensed areas, what is likely to result in more efficient decision making. Furthermore, the mapped placemarks are clickable on Google Earth, allowing decision makers to see detailed information of each stress event, such as intensity and description.

VI. CONCLUSION

We proposed an interdisciplinary methodology for assessing sources of stress in professional bus drivers based on the population's real world needs. The system was designed by an interdisciplinary team, in cooperation with bus drivers working in the city of Porto. The method validation was tested among a sample of bus drivers in their day-to-day routine.

Results showed that the methodology is successful in detecting stressful events based on bus drivers' physiologic responses. Furthermore, the system provides real world visual cues and information, which seems to facilitate driver memory retrieval, enriching description of stressful events, and findings provide contextualized sources of stress within a city. Applied implications of this method will foster evidence based solutions at enterprise, policy-makers and government levels, providing an open approach to improvement and change towards developing bus drivers' occupational health, improving driver performance, and enhancing overall road safety. Theoretical implications of this paper also include contributions to the stress assessment literature in general and particularly to the occupational health.

Findings provide strong theoretical and practical implications. Respectively, the method makes a valuable contribution to the occupational health stress assessment literature. Additionally, practical implications will facilitate the design of holistic occupational health interventions for bus drivers while also guiding authorities interventions aiming to increase road safety. Current ongoing work is deploying this methodology over a larger population in order to perform a comprehensive characterization of sources of stress among professional bus drivers in the city of Porto.

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A Mobile Sensing Approach to Stress Detection and Memory Activation for Public Bus Drivers

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***Abstract*—The experience of daily stress among bus drivers has shown to affect physical and psychological health, and can impact driving behavior and overall road safety. Although previous research consistently supports these findings, little attention has been dedicated to the design of a stress detection method able to synchronize physiological and psychological stress responses of public bus drivers in their day-to-day routine work. To overcome this limitation, we propose a mobile sensing approach to detect georeferenced stress responses and facilitate memory recall of the stressful situations. Data were collected among public bus drivers in the city of Porto, Portugal (145 h, 36 bus drivers, +2300 km), and results supported the validation of our approach among this population and allowed us to determine specific stressor categories within certain areas of the city. Furthermore, data collected throughout the city allowed us to produce a citywide "stress map" that can be used for spotting areas in need of local authority intervention. The enriching findings suggest that our system can be a promising tool to support applied occupational health interventions for public bus drivers and guide authorities' interventions to improve these aspects in "future" cities.**

***Index Terms*—Public transportation, driver, stress detection, wearable technologies, georeferenced data analysis.**

I. INTRODUCTION

DRIVER behavior constitutes a major concern in road safety research and policy. Since buses are one of the most used modes of public transportation worldwide, the behavior of bus drivers and their occupational health becomes a critical priority in overall road safety [1].

Epidemiological evidence from several studies conducted mainly in North America and in Western Europe showed that urban bus drivers have substantially higher mortality rates and higher risk to develop physical and psychological diseases in comparison to many other occupational groups [2]. In agreement with this findings, a meta-analysis by Tse *et al.* [1] reviewing fifty years of research in the area of bus driver well-being concluded that this population is exposed to several sources of stress over time. These can be distinguished in three main categories: physical environment, job design and organizational issues. Physical environment includes sources of stress related with cabin ergonomics, exposure to noise, weather conditions, threat of physical violence, and traffic congestion aspects. Job design includes responsibility for security and schedule obedience, working in shifts, long periods of social isolation, ticket selling and control. Organizational issues are related to bus drivers low autonomy and limited decision-making authority. Finally, bus drivers profession is associated with high sedentarism levels, which is known to be a major cause for cardiovascular diseases [3].

The task of driving involves considerable strain for bus drivers, ranging from the needed awareness to safeguard passengers, to traffic hazards [4]. The diversity of daily demands faced by this population causes detrimental effects to their physical and psychological health and well-being, as supported by studies conducted in the occupational [5], ergonomic [6] and biomedical areas [7]. Furthermore, it can also increase the risk of accidents, decreasing overall road safety [1]. Also, stress caused by emotional upsets has been associated with several incidents among drivers [8]. This is probably explained by the fact that emotional states of anger and frustration can increase driver distraction and impair driving performance [9]. Additionally, bus drivers role is often conceptualized as high in demands (i.e., traffic congestion, rotating shift patterns, negative passenger interaction, tight running times, workload demands, etc.) and low in control with respect to limited decision latitude [6]. This is a main cause for psychological problems [2] and cardiovascular diseases [10].

In agreement with this idea, an investigation by Baevskii *et al.* [7] aiming to study the use of principles of prenosological diagnosis for assessing the functional state of the body, has found that bus drivers experienced chronic occupational stress leading to exhaustion of regulatory mechanisms and to rapid development of cardiovascular pathology. As explained by the authors, long-term mental and psychoemotional tension in bus

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drivers was associated with occupational stress, and leads to the worsening of psychophysiological and cardiorespiratory function of the body. The degree of stress was assessed in this study based on analysis of Heart Rate Variability (HRV).

While there is no definitive method of directly assessing physiological stress levels, many techniques have been identified in the literature, such as heart rate and HRV metrics, electrodermal activity, respiration rate, electromyography and blood volume pressure [11]–[14]. Their results suggest that stress events do indeed cause a reaction perceivable in physiological signals, and that using multiple physiological inputs and incorporating driving event information can greatly increase drivers' stress detection accuracy [15], [16].

Although, one can question the ecological validity and reliability of driver stress measures collected in laboratory conditions [17]. In opposition, stress assessment research among drivers should take place in ecological settings including non-intrusive physiologic stress monitoring. Recent advances in noninvasive measurement techniques allowed the progression of human developmental stress research [18], including ambulatory monitoring of cardiovascular function [19]–[21]. HRV can be calculated from the Electrocardiogram (ECG), and is reported to be an accurate measure of stress [13]. Recent studies were able to correlate stress with some non-linear HRV features [22], while time-domain and frequency-domain features extracted from HRV have been validated multiple times as stress indicators in the last decades [13], [14], [23].

Nevertheless, stress assessment in ecological settings among bus drivers is not always an easy task, mainly due to difficulties faced when aiming to collect their physiologic and psychological stress responses during operation of public vehicles in urban centers [24]. Previous research in this area [25], [26] associated physiologic (e.g., blood pressure levels, pulse, and urine samples) and psychologic (e.g., self-report and/or researchers observation) measures of stress, and data was collected during bus drivers rest periods. Although these studies provided a crucial contribution to the understanding of daily stress among bus drivers, they are plagued by limitations highlighted below. Primarily, physiologic measures used do not include HRV, considered to be one of the most viable physiologic assessments of stress [14], [23]. Secondly, these research designs failed to understand the physiologic and psychologic impact of a specific source of stress on the driver [27]. Thirdly, the retrospective self-report assessments of sources of stress at the end of a working day may be plagued by attention and memory bias, limiting the driver ability to recall acute stressful events [28]. It is well known that the experience of stress affects quality of memory recall [29]. Furthermore, bus drivers deal with numerous tasks and challenges throughout a day at work (e.g., driving, interaction with passengers and other drivers). Hence, previous research has shown significant discrepancies between real-time assessments and retrospective recall [30], questioning how accurate and valid are results that rely merely on bus drivers memory construction and retrieval.

Towards this goal, the current paper proposes an interdisciplinary method that combines physiologic, psychologic and georeferenced data to investigate sources of stress faced by bus drivers while driving in an ecological setting on a daily work basis. Our contribution includes the design of stress assessment software, adapted to the routine needs of bus drivers, and combines non-intrusive, user friendly and reliable physiologic and psychologic research methods, providing a continuous daily monitoring of the driver during the course of a day at work. To overcome previous retrospective self-report assessments among bus drivers, our methodology provides a digital contextualization of potential sources of stress, including environmental cues to trigger memory retrieval [31]. Furthermore, this information is synchronized with the physiologic response for each stressor and the georeferenced location.

Hence, findings will benefit future evaluation of stress sources among bus drivers and will foster the design of efficient occupational health and local road safety interventions.

II. METHODOLOGY

In this section we describe the technology and methodology that was iteratively improved by real-world experiments with professional bus drivers in the city of Porto, Portugal.

A. *Sensing Platform*

Our project targeted a large population, and thus our platform was designed to be very easy to use and have very low intrusiveness. These were critical for the wide acceptance and participation we achieved, with 36 volunteers out of 37 drivers introduced to the project.

1) Physiologic Sensors: One kit of equipment was provided to each bus driver, including a VitalJacket,[1] disposable electrodes, a Global Positioning System (GPS) receiver and a netbook PC. The Vital Jacket (VJ) is a wearable bio-monitoring platform in the form of a t-shirt that provides real time electrocardiogram (ECG) with 500 Hz sampling rate, 3 axis accelerometer and an event push-button [21], [32]. This data is transmitted to the netbook via Bluetooth from a small box embedded in an easily accessible pocket on the t-shirt.

2) Self-Report Measures: Health and demographic questionnaires were completed by participants. This data was used to analyze the impact that demographic metrics have on the drivers' physiologic response (Section IV-C).

Furthermore, bus drivers provided a description of each potential stressor, followed by a stress intensity rating, based on their appraisal of the particular situation. Potential stressful situations were either detected by the system or tagged by the drivers using the push-button incorporated in the VJ. Stress intensity was assessed using a "stress thermometer" where the participant dissected a 10 cm bipolar line anchored by two statements ("not at all stressful" vs. "extremely stressful"). The "stress thermometer" has demonstrated normal distribution properties and adequate variability in previous stress assessment research [33], [34].

3) System Architecture: The GPS receiver used was placed near a bus window and transmits information to the netbook via Bluetooth. A small and lightweight netbook, chosen for its

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[1] BioDevices S.A., www.vitaljacket.com.

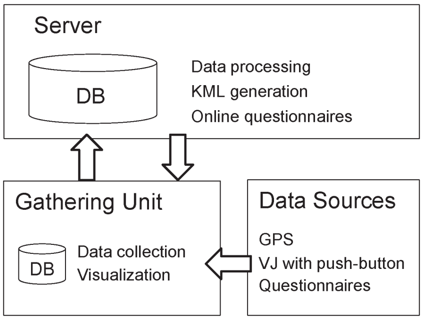

Fig. 1. Hardware architecture.

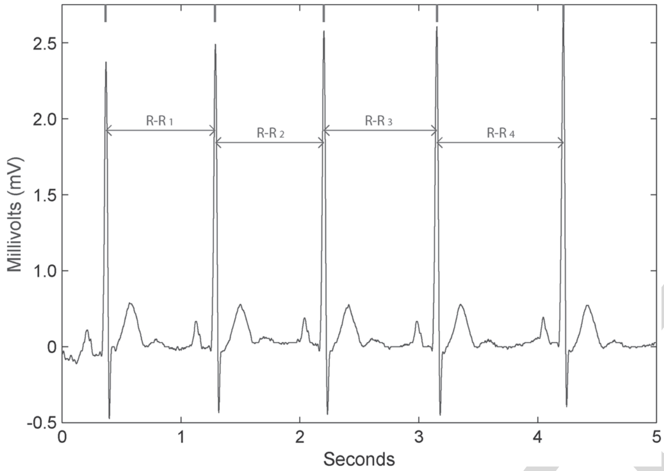

Fig. 2. Sample ECG signal collected from a bus driver and R-R measures.

portability, served as the gathering unit. Data processing was performed on a cloud server to increase processing speed. The netbook was used further for visualization in the recall phase (see Section II-B), and the required Internet connectivity was provided by a 3G network adapter.

The architecture of the system designed and implemented to integrate the previous materials is shown in Fig. 1. This architecture and gathering capabilities, such as sensor-data synchronization, reliability and communications have been tested and validated in previous work [35].

4) Signal Processing Software: The processing of the ECG signal was performed using the open-source library PhysioToolkit from Physionet [36], which follows the recommendations proposed by the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology [13].

We used the GQRS tool from the library to extract heartbeat information from the ECG. Fig. 2 shows a 5 second ECG segment with the R peaks marked at the top. This tool determines the moment of the peaks for each heartbeat and outputs the inter-beat intervals (R-R) in a format compatible with other Physionet tools.

Extra processing and filtering of the cardiac signal was required, as explained in Section III-C, due to the presence of very noisy signals, which can occur in real world research.

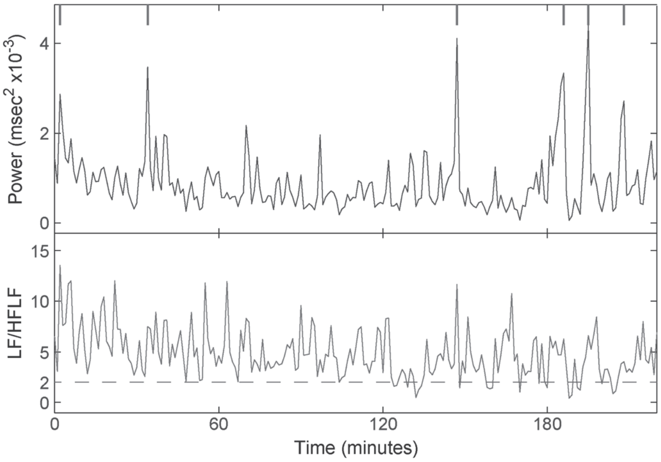

Fig. 3. Low Frequency Power and the ratio between Low Frequency and High Frequency power, for a 3 hour long trip. We use the standardized LF Power to detect stressful events, marked in the top horizontal axis.

We used the HRV Toolkit from Physionet to perform time-domain and frequency-domain analysis of the heart rate information, as suggested by the Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology [13]. We performed the analysis using a window size of 100 s with a shift of 60 s between consecutive windows, and the results were stored for further statistical analysis (which we denominate HRV blocks). We decided to use overlapping windows to improve the time accuracy of the results, but we downsample the results when independence between samples is required (see Section III-C). The window size of 100 s was chosen in order to have a 0.02 Hz of frequency resolution in the frequency-domain results without upsampling. Among others, the metrics include the average normal-to-normal (NN) intervals, the standard deviation of these NN intervals, their low frequency spectral power (LF) between 0.04 Hz and 0.15 Hz, the high frequency power (HF) between 0.15 Hz and 0.4 Hz, and the ratio LF/HF.

The spectral power of different frequency bands is specially important to our study, because the power in the HF band is mainly mediated by the parasympathetic system and encompasses respiratory sinus arrhythmia, but the LF band is mediated by both the parasympathetic and sympathetic components, and so they might provide a robust way to assess individual stress [37]. Fig. 3 shows an example of the evolution of the LF power and the LF/HF ratio, which are the two metrics most correlated to stress according to [12] and [23]. The figure shows that spikes are more distinct in the LF than the LF/HF case. A statistical analysis (Section III) confirmed this, leading us to use the LF power as a stress indicator.

5) Detecting Stressful Events: Potentially stressful events were selected from all the moments the driver pushed the button on the VJ, combined with additional 10 blocks with the driver's highest physiologic stress (LF component) but separated at least 5 minutes between each other.

6) Enquiry and Visualization Tools: The processed ECG data, together with the GPS information, was used to generate a map at the end of each driver's shift.

Fig. 4. Visualization of a trip and stress events in Google Earth. The height of the traces represents bus speed, ellipses denotes events.

The map was visualized using Google Earth (Fig. 4), providing a straightforward approach to overlay spatial data and correlate different types of information. Free camera movements and a time toolbar, used to select a time interval window to be displayed, allowed to easily analyze the detected events and their context. To facilitate memory recall, we overlaid information about location and time of the events, as well as the speed of the bus in the whole trip, plotted using a line segment over the map with the height of the line representing speed. By displaying the speed profile for every second of the trip, the driver and researcher could easily identify bus stops and driving events information, such as aggressive braking, accelerations (as in Rigas *et al.* [16]) and others, aiding them recall and characterize the events. In the map, the detected potentially stressful events were displayed as ellipses spanning over the area traveled during the corresponding 100 s HRV block.

The Internet connection from the 3G network adapter was used to access Google Earth and refresh the maps and to synchronize the driver's self-report data to the server. Moreover, the netbook also leveraged this Internet connection to speed up the processing of the ECG signal, sending the raw data to a server that performed all the needed computation and generated the maps. This upload and cloud processing took around 4 minutes for a 6 hour work shift. If the computation had been done locally, it would have taken around 15 minutes for the same workload.

B. Procedure

On the day prior to data collection, participants completed a demographic and health questionnaire, and received a kit containing the required equipment. At this time they were given a detailed explanation of the procedures by a researcher. On the data collection day, the bus driver followed the workflow depicted in Fig. 5, wearing the VitalJacket and turning on the netbook and GPS receiver at the beginning of the work shift. Following this procedure, the bus driver was ready to start his work shift, carrying the kit for a full day. The participant was instructed to press the button on the VitalJacket in case of appraising a potentially stressful event during the day, affecting his or the passengers well-being. At the end of the shift, a researcher met the participant at the station, and ran the cloud processing algorithms over the gathered data. A map was then produced displaying the information for the full workday of that participant, as described in Section II-A6.

For each of the displayed ellipses, the driver visualized the exact location and extra information using Google Earth (Fig. 6). For the cases when the participant could remember the event, he was asked to recall that particular situation, and to provide a brief description followed by the stress intensity evaluation for that particular event. The description of the events and stress intensity evaluation were completed in the netbook, but stored and synchronized with the physiologic data on the cloud server.

The protocol was designed to obtain the following independent data sets to help in the detection and categorization of the events:

- Tagged events, providing annotations of on-site self-reported stressors including a description of the situation experienced and stress intensity evaluation;
- Physiologic responses measured with biomedical sensors—HRV blocks;
- Location and velocity information assessed from GPS data, used to detect driving events and facilitate memory retrieval.
- Short annotations for every stressful event detected by the system and confirmed by the driver as stressful, including a description of the situation experienced and stress intensity evaluation.

This method provided an accurate connection between the georeferenced data, description of the stressor experienced and stress appraisal evaluation for a particular stressor, synchronized with physiologic and driving response data. The ellipses provided a general vicinity to the memory retrieval of the event, contextualizing time and location information. Additionally, the method allowed the driver to isolate certain events during the working day by pushing the button. These were saved in the system and available for description and stress intensity evaluation later at the end of the work shift.

III. DATA ANALYSIS

A. Samples and Population

Thirty-six male professional bus drivers, aged between 29 and 55 years old (Mean = 41; Standard Deviation = 6.5) with experience in bus driving between 3 and 25 years (M = 13; SD = 6.0), participated in this study. All participants worked for the major transportation company in the city of Porto, Portugal. The exclusion criteria for the study were participants having a history of cardiovascular disease and/or taking prescription drugs known to affect cardiovascular function. Participants volunteering to participate in the study were instructed to perform no changes in their daily routine, such as sport activities and caffeine, nicotine and food consumption.

Following approval of the study by the bus company administration, bus drivers were invited to participate. For this purpose a presentation session was organized by researchers, explaining the aim and protocol of the study. Participants provided informed consent forms prior to participation.

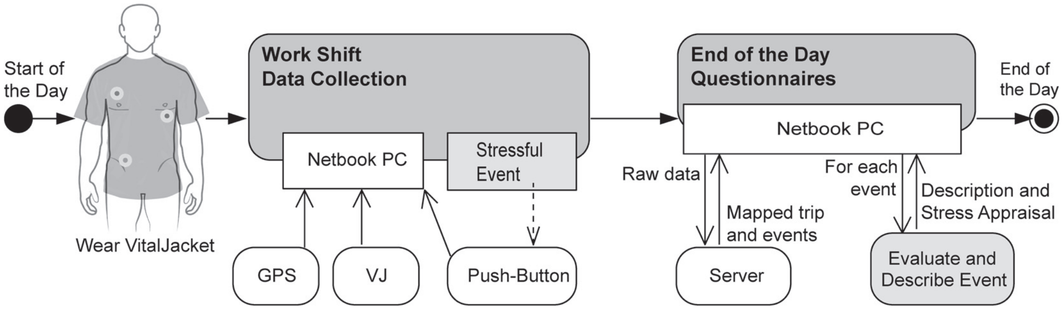

Fig. 5. Workflow on daily data collection.

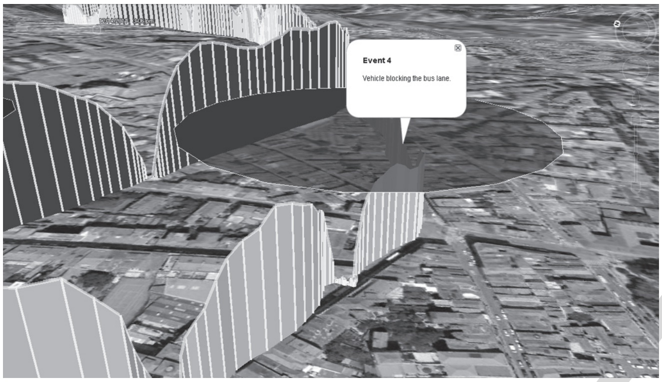

Fig. 6. Close-up of a stress event in Google Earth. The height of the traces represents bus speed.

Data was collected for each bus driver over a full working day, corresponding to approximately 5 hours of driving, divided in one or two daytime shifts occurring between 8 AM and 8 PM. In total, this study gathered 151 hours of data, including 500 Hz ECG and location information stored every second that spanned more than 2.500 kms.

B. Stressor Categories

Each situation of stress described by the drivers in the 86 events was subjected to a content analysis to identify stressors categories. The identified categories are similar to a great extent to the job hassles reported by previous research [27], with a few exceptions discussed in Section V.

The first two authors then independently assigned each event into 5 major stressor categories or event types.

1) Social interactions (e.g., with passengers or friends);
2) Unexpected situations (e.g., mechanical failures, driving mistakes, unexpected changes);
3) Other drivers or pedestrians behaviors (e.g., other drivers risky behaviors and lack of politeness);
4) Events that impact time schedule (e.g., traffic congestion);
5) Difficult driving due to urban planning (e.g., narrow roads and tight corners).

A reliability check showed a level of agreement of 98.8% between both researchers after the first categorization. Following some discussion, this agreement increased to 100%.

C. Filtering and Processing the Physiologic Data

1) Synchronizing the VJ and GPS Clock: The Physionet library can process the cardiac signal and outputs the metrics we need. However, some extra steps were required in order to synchronize the Physionet output with our GPS data.

We used the GQRS tool from Physionet to detect heart beats, which takes the ECG signal as input with a specified starting time and sample frequency, and outputs the timestamps of every detected beat. Even though the VitalJacket, our ECG sensor, has a fixed 500 Hz sampling rate, small errors in the VJ clock precision and in the Bluetooth communication can cause discrepancies between the timestamps and duration of the ECG and the GPS data. This clock drift is negligible at the beginning of a trip, since a starting timestamp is given to the application, but naturally increases as the time passes, and sometimes resulted in errors of more than 15 minutes at the end of the 6 h trips in our pilot experiments. A small desynchronization between the VJ and GPS clocks can cause a huge misplacement of a stressful event, since buses can travel at up to 50 km/h (14 m/s)

To correct this synchronization issue our processing algorithm keeps track of the GPS clock and also of a virtual one that follows the beat-detector fixed 1/500 s per data sample. The differences between both clocks is constantly analyzed, and the ECG stream is split and given a new corrected timestamp every time a shift of more than 10 s is detected.

2) Detecting Noisy ECG Data: Another problem we detected in our pilot experiments when processing the data was ECG noise. The heartbeat detectors perform poorly in the presence of very noisy signals that can occur in real world scenarios like ours, leading to the detection of false-positive stressful events. There are many sources of noise in a real world environment, such as from other muscular activity or electrode misplacement, which can significantly reduce the accuracy of the heartbeat detection algorithms.

We implemented a Standard Deviation (SD) filter to detect extremely noisy blocks of data and improve the reliability of the ECG data. This filter calculates the SD of the raw ECG every second (500 samples), discarding an HRV block from the analysis if it contains any second with an SD higher than a threshold. The filter successfully detected the trips belonging to 2 drivers who misplaced the electrode patches, and also other 3 trips that presented problems with the electrodes' connection after some point in the middle of the trip. After analyzing these trips, the threshold was set as the 90th percentile of all of our data, eliminating the 10% noisiest ECG data gathered in our real world scenario. The SD filter was applied to 151 h of gathered data, resulting in 1470 discarded HRV blocks. From these, 1349 (92%) belonged to 5 trip segments with problems in the electrode patches.

3) Push-Button Time Correction: Another filtering step was the correction of tagged events' timestamps. This consisted in correlating the push-button events with the correct HRV block of physiologic sensor data by analyzing the driver description of the event and surrounding trip data, such as location and speed. Most of the events were associated with the block that immediately preceded it, meaning that the drivers pressed the button right after they experienced a stressful situation. However, in some cases they were associated with the following block, because some drivers pressed the button when approaching a known dangerous place.

4) HRV Metrics Standardization: Different drivers have different cardiac characteristics and baselines, preventing us from comparing HRV metrics between multiple drivers. Since we could not collect a baseline for each driver in a relaxed and controlled environment, we decided to standardized the cardiac metrics per driver. To this end, the HRV metrics of each driver's entire collection day were transformed to have zero mean and unit variance.

5) Downsampling to Independence: The final step in our processing algorithm was the downsampling of the HRV blocks for each driver in order to increase independence between samples. The recalled events were already selected with at least 5 min of data between them. However, the rest of the ECG was analyzed every minute but with a window size of 100 s, resulting in 40 s overlap between HRV blocks, and producing a dependent dataset of HRV metrics. To make the HRV blocks independent, the processed and filtered blocks were downsampled for each driver, removing the minimum number of blocks that guarantees the same 5 min distance between HRV blocks or any recalled or tagged events.

IV. RESULTS

We gathered a total of 9081 HRV Blocks, from which 1470 were filtered as noise and 6050 were removed in the downsampling process. From the 36 drivers, 2 had misplaced electrodes providing no useful ECG data and other 2 forgot to turn on the GPS device. 29 events were tagged on-site as stressful by 11 drivers. Some drivers forgot they were being monitored and thus forgot to press the button in stressful situations, others were distracted dealing with the situations.

To facilitate the events recall, 320 distinct blocks were identified by the system and shown to the 32 drivers in the map at the end of the day. From these, 57 blocks were recalled as stressful events and evaluated by 27 bus drivers, 2 drivers did not recall any additional events besides the ones they tagged, and 3 stated they did not experience any stressful situations during their work shift.

Our final dataset to be analyzed contains stress information from 29 drivers, with 29 on-site tagged events, 57 events recalled at the end of the day, and other 1475 HRV blocks not identified as stressful. Thus, a total of 1561 independent rows of data standardized per driver.

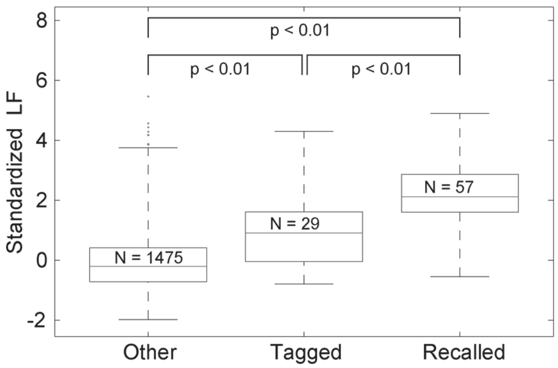

Fig. 7. Distribution of calculated stress between other blocks, tagged events, and events recalled at the end of the day.

Due to non-normalized distributions of the data, we used non-parametric tests. The Mann-Whitney U-Test [38] was chosen to compare the distributions of two populations, the Kruskal-Wallis Test [39] to verify if more than two populations have the same distributions, and the Kendall's Tau [40] to check for statistical dependence between variables in the same population. To this end, multiple pairwise MannWhitney U-Tests were conducted to analyze differences in the main HRV metrics between the samples classified as tagged events, recalled events and others. Kruskal-Wallis Test was conducted to test for differences in the LF spectral power across stressor categories in both self-reported and cardiac stress responses. Kendall's Tau rank correlation test was used to search for statistical association between demographic and physiologic variables.

A. Physiologic vs Recalled Stress Assessment

Our system used the LF component of the interbeat intervals as a stress indicator, as proposed by [12] and [23]. To validate this proposition, we compared the LF frequency component of all blocks, the tagged events and the stress events recalled at the end of the day (Fig. 7).

The MannWhitney U-Test showed significant difference between the distributions of LF power for other and tagged events ($z = -4.91$, $p = 9.16^{-7}$), indicating that there is a significant increase of the LF power during events appraised as stressful by the driver. The recalled events also presented a statistically higher LF component than the tagged events ($z = -4.85$, $p = 1.23^{-6}$), even when analyzing only the 11 drivers who tagged events.

The same statistical analysis between tagged and other events was performed for every HRV metric, and some are presented in Table I. The metric that showed the most statistically significant difference was the LF power, followed by the time-domain metrics that detect variability, such as standard deviation of heart beat intervals.

TABLE I
DISTRIBUTION TESTS' RESULTS BETWEEN OTHER AND TAGGED EVENTS OF DIFFERENT HRV METRICS FROM THE HRV TOOLKIT

MannWhitney	AVNN	SDNN	pNN50	LF	HF	LF/HF
Z value	-0.68	-4.19	-2.75	-4.91	-2.39	-1.42
P value	0.50	< **0.01**	< **0.01**	< **0.01**	**0.02**	0.16

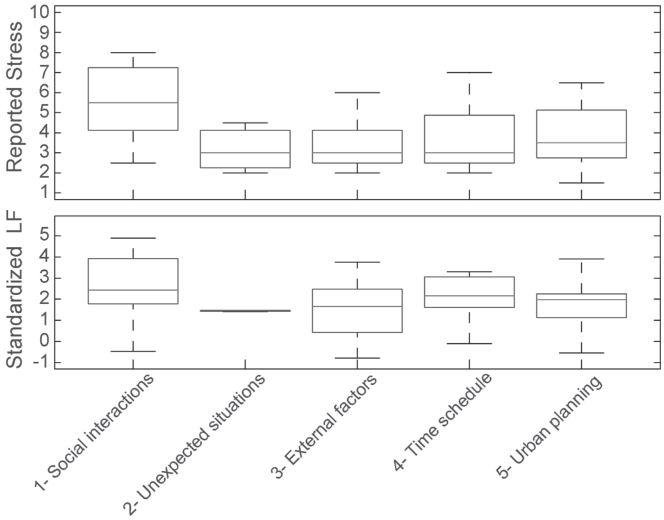

Fig. 8. Distribution of the stress level throughout the different stress categories, for both reported stress evaluated by the stress thermometer, and calculated from the ECG signal.

TABLE II
FREQUENCY ANALYSIS FOR REPORTED STRESSOR CATEGORIES: NUMBER OF REPORTS, FREQUENCY RELATIVE TO THE TOTAL NUMBER OF EVENTS, NUMBER OF DISTINCT DRIVERS THAT REPORTED THAT CATEGORY, AND CORRESPONDING RELATIVE FREQUENCY TO THE NUMBER OF DRIVERS

Stressor Category	1	2	3	4	5	Total
Total Count	14	7	30	16	19	86
Relative Frequency	16%	8%	35%	19%	22%	
Drivers	11	6	18	12	12	29
Drivers Frequency	38%	21%	62%	41%	41%	

B. Analysis of Stressor Categories

Fig. 8 shows an overview of the distributions for physiologic and self-reported stress intensity evaluation for each stressor category, introduced in Section III-B. An event was only considered to be stressful when appraised by the bus driver as higher than 0 in the stress thermometer scale (51 of the 86 identified events).

The Kruskal-Wallis Test showed that no significant differences across stressor categories exist either for self-reported $X^2(4, N = 51) = 7.62; p = 0.11$; or for cardiac stress responses $X^2(4, N = 51) = 4.82; p = 0.31$.

Table II shows a frequency analysis of stress categories combining all tagged and recalled events appraised as stressful by bus drivers. Other drivers or pedestrians behaviors were the most commonly reported source of stress, reported for 35% of the recalled or tagged events and mentioned at least once by 62% of the 29 bus drivers. Difficulty driving due to urban planning was the second most reported source of stress, reported for 22% of the events recalled or tagged, and mentioned by 41% of the drivers (12/29). Also, events that impact time schedule was a frequently reported source of stress, accounting for 19% of the events and mentioned by 41% of the drivers.

TABLE III
KENDALL'S TAU TEST RESULTS FOR DEMOGRAPHIC AND FULL-DAY CARDIAC METRICS. P VALUES LOWER THAN 0.05 ARE MARKED AS BOOLEAN

	Age		Weight		Experience	
	Tau	P	Tau	P	Tau	P
AvgAVNN	0.0	0.84	0.3	0.06	-0.3	**0.02**
AvgSDNN	0.0	0.87	0.1	0.72	-0.3	**0.01**
AvgLF	-0.1	0.32	0.1	0.63	-0.3	**0.04**
AvgHF	-0.2	0.09	0.1	0.45	-0.3	**0.02**
AvgLF/HF	0.1	0.37	-0.1	0.72	0.0	0.93

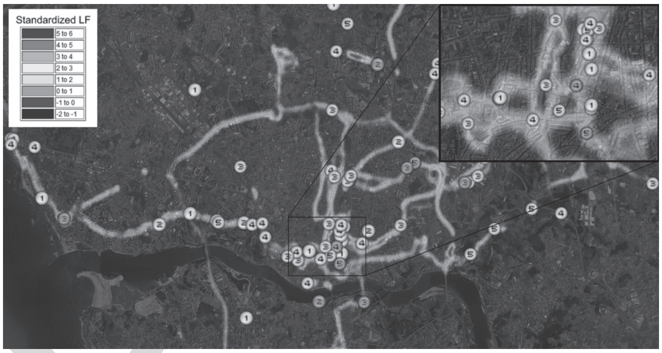

Fig. 9. Stress map of Porto with placemarks on detected stressful events. The numbers represent the event category, the darker marks are tagged events and lighter are events recalled at the end of the day.

C. Questionnaires and per Driver Analysis

In this project we also analyzed the questionnaires data and their correlations with the cardiac metrics. We combined the questionnaires answers with the HRV analysis over each driver's full dataset, resulting in metrics such as a driver's age, height, weight, years of experience as a bus driver, usual exercise routine, and also the full day's average heart rate, average spectral power for different frequencies, and others.

To analyze the data we performed cross-correlation analysis between all variables using Kendall's Tau (τ) rank correlation test [40]. The main results are presented in Table III, with correlated variables resulting in a p-value lower than 0.05 marked in bold.

The results show a strong correlation between the cardiac metrics and the years of experience of the drivers, and not with any other demographic metric.

D. Geo-Referenced Stress Analysis

Furthermore, the analysis of the tagged and recalled stress events showed that more than 75% (65/86) of the stressors are location-dependent, such as tight roads, low-visibility crosswalks and drivers not respecting signalization on some crossroads. This data suggests that the geographic reference of detected events provided by our method was efficient in facilitating bus drivers' memory retrieval, and also that it is possible to provide valuable stress-maps to decision makers. With both physiologic and psychologic stress assessment performed with our methodology, we are able to map their intensity and detect systematically stressful locations.

Fig. 9 shows a stress map of the city of Porto, where lighter areas represents less stressful and darker areas represents highly stressful places. Also, darker symbols mark the spots where stressful events were tagged, lighter ones were recalled at the end of the day, and the numbers correspond to the event category as stated in Section III-B. The map was generated by clustering and averaging the Standardized LF information of the HRV blocks. Additionally, in order to eliminate biases in the cardiac data associated with physical activity, we discarded data gathered while the bus was almost stopped (less than 5 km/h) and only map clusters with data from at least 3 distinct drivers.

Based on Fig. 9 it is clear that the city downtown, near the center of the map, is a stressful region with many highly-stressful roads being detected in that dense urban zone. However we can also find other less obvious highly-stressful zones, such as in the left-middle edge of the map, where a roundabout caused a cardiac response in all of the 4 drivers that passed by and even a tagged event from one of the drivers.

V. DISCUSSION

The aim of the current paper was to investigate daily sources of stress faced by bus drivers while driving in an ecological setting during their daily work. Results suggest that the proposed method is accurate in detecting psychological and physiological stress responses. Despite the divergence in the concept definition and assessment of stress, our findings are consistent with previous research recommendations [41].

Particularly, results showed a significant increase of the LF component of HRV during events appraised as stressful by the driver, suggesting that the stress concept assessment can combine both psychologic and physiologic dimensions of stress, while also contemplating an integrative approach in the real world. Contrary to the results presented by McCraty *et al.* [12] and Healey and Picard [23], the LF/HF does not show a statistically different distribution between tagged stressful events and other HRV blocks, which may be due to the higher HF noise present in real word scenarios like the one in this study. This indicates that the LF power is the best stress metric for our scenario.

Regarding demographic factors and their impact on the drivers' physiologic response, results indicate that years of experience of the driver is an important factor to consider. Surprisingly, even the age, which is correlated with the years of experience, is not significantly correlated with the physiologic metrics. This suggests that, although cardiac response is known to decrease with age [42], more experienced drivers (not necessarily older ones) have less cardiac response to stressful events and a smoother physiologic response throughout the entire working day. Further research is required controlling for bus drivers routes in order to confirm whether this finding is due to effective coping strategies developed by this population or the experience of different environmental demands.

In what concerns to sources of stress found in our study (Section III-B), these are similar to a great extent to the job hassles reported by Johansson *et al.* [27] among bus drivers working in the city of Stockholm (e.g., traffic congestion, illegal parking of vehicles, risky or impolite behaviors of other divers or pedestrians, mechanical difficulties, timetable restrictions). However, in the current study, social interactions with passengers or friends and bus driving mistakes were also reported as stressors in 16% of the reported events and by 38% of the drivers (11/29). We believed that this fact may be mainly related to the methods used in this study that facilitated the drivers memory retrieval of events. On the other hand, previous research methods used across studies relied on retrospective self-reports following long periods of time what may had affected the type of stressors reported. Additionally, other previous studies were based on the researcher observations, whereas our study relied on a more ecological setup and based on the inputs of the drivers themselves, i.e. their own perceptions and experiences of stress. As a result, stress categories such as the experiences of interpersonal stressors are unlikely to be reported by others, who merely described what they can observe. Also, the constant presence of an observer may produce biased results, making the driver less likely to do driving mistakes and avoid communicating with friends entering the bus. Hence, we believe that the type of stress categories found in this study complements the literature in the area and reinforce the strengths of the methodology used to capture drivers acute stressors experienced on a daily basis.

It is important to highlight that the current ecological method culminates a previous limitation in the area of stress reactivity assessment [43], and provides a crucial contribution to the study of cardiovascular reactivity to stress in real world scenarios. This is a fundamental relationship when investigating sources of stress, critical to the etiology of cardiovascular disease [27]. Furthermore, as suggested by Myin-Germeys *et al.* [44] stress responses assessed in real life situations are more likely to be closer to reality than those collected under laboratory settings.

Additionally, the inclusion of georeferenced information and its visualization by bus drivers was a key aspect in this methodology, facilitating memory retrieval of the experienced situations, thus providing a detailed description and specificity of stressors. To support this argument the proposed methodology allowed the collection of 57 additional stressors in the city of Porto, compared with only 29 voluntarily tagged by bus drivers.

In sum, the proposed methodology provides detailed information of different stressors experienced by bus drivers, and their specific location in a city. It is believed that this information can induce evidence based decisions across a variety of areas (e.g., ergonomics, security, management, technological, public policy, psychologic and urban planning). Additionally, the system is able to map exactly where in the city these events have occurred and the average stress intensity for the sensed areas, what is likely to result in more efficient decision making. Furthermore, the mapped placemarks are clickable on Google Earth, allowing decision makers to see detailed information of each stress event, such as intensity and description.

VI. CONCLUSION

We proposed an interdisciplinary methodology for assessing sources of stress in professional bus drivers based on the population's real world needs. The system was designed by an interdisciplinary team, in cooperation with bus drivers working in the city of Porto. The method validation was tested among a sample of bus drivers in their day-to-day routine.

Results showed that the methodology is successful in detecting stressful events based on bus drivers' physiologic responses. Furthermore, the system provides real world visual cues and information, which seems to facilitate driver memory retrieval, enriching description of stressful events, and findings provide contextualized sources of stress within a city. Applied implications of this method will foster evidence based solutions at enterprise, policy-makers and government levels, providing an open approach to improvement and change towards developing bus drivers' occupational health, improving driver performance, and enhancing overall road safety. Theoretical implications of this paper also include contributions to the stress assessment literature in general and particularly to the occupational health.

Findings provide strong theoretical and practical implications. Respectively, the method makes a valuable contribution to the occupational health stress assessment literature. Additionally, practical implications will facilitate the design of holistic occupational health interventions for bus drivers while also guiding authorities interventions aiming to increase road safety. Current ongoing work is deploying this methodology over a larger population in order to perform a comprehensive characterization of sources of stress among professional bus drivers in the city of Porto.

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AUTHOR QUERY

NO QUERY.