Multimodal Transportation 4 (2025) 100185

Contents lists available at ScienceDirect

Multimodal Transportation

journal homepage: www.elsevier.com/locate/multra

Full Length Article

Analysis of the driver's stress level while driving in Truck Platooning

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ARTICLE INFO

Keywords:
Truck platooning
Stress level
Driving test
Heart rate variability (HRV)
Driver
Safety
Wearable devices

ABSTRACT

The logistic is interested by changes and truck manufacturers are investing in solutions such as truck platooning. This system leads to benefits (fuel consumption, safety, traffic efficiency). The paper presents the analysis of the psychophysical state of drivers during real tests in truck platooning. The peaks in the LF/HF (Low Frequency/High Frequency) parameter are considered, as they are linked to feelings of discomfort. Their occurrence may indicate whether the psychophysical state of the drivers is influenced by the different phases of driving in platoon. A method is defined to monitor and process the HRV (Heart Rate Variability) physiological parameter and the LF/HF ratio, based on the use of commercial smartwatches. An experimental activity, part of the European project C-Roads, allowed the collection of the physiological parameters of drivers and of the data featuring the vehicles in platoon. In general, the correlation between the two data sets revealed that drivers were not negatively affected by driving in platoon. The monitoring of the Follower driver, compared to the Leader, showed a higher level of stress. Peaks in the LF/HF parameter (i.e. high levels of stress) were associated in the 85 % of the cases to punctual situations that were expected to be stressful. Further possible applications of the method are presented, such as the investigation of the C-ITS impacts on the drivers.

1. Introduction

The sector of logistic is currently interested by important changes. In this wide framework of innovations and developments, the truck manufacturers are investing resources in the Truck Platooning system, as prodrome of autonomous driving for heavy vehicles. Truck Platooning is defined as a set of vehicles moving in a coordinated way (Al Alam et al., 2010; Agriesti et al., 2021) and communicating between each other. Using the Cooperative Adaptive Cruise Control (CACC), the Leader vehicle transmits information about its driving state, such as acceleration, position and instantaneous speed to the Followers vehicles. Knowing this information, the Followers vehicles adapt their driving avoiding the risk of collisions, despite the reduced inter-vehicle distance. The possibility to adopt these reduced distances is made possible by the automated longitudinal control of the vehicles entrusted: drivers are partially disengaged (still responsible for the transverse control of the vehicle) and therefore the human reaction time is annulled. The Truck Platooning system allows the mitigation of the stop-and-go waves (Caruntu et al., 2014), determining positive impacts on road safety and traffic efficiency (Studer et al., 2019). At the same time, one of the highest benefits of the reduced inter-vehicle distance is the decrease of aerodynamic resistances and therefore a lower fuel consumption (Agriesti et al., 2018). Tests and studies allowed to consider the system as technologically mature, with the development of solutions that operate in fail-safe and therefore that ensure safety even in case of malfunction of a component. This maturity is a necessary but insufficient condition to the actual wide-scale

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https://doi.org/10.1016/j.multra.2024.100185
Received 28 June 2024; Received in revised form 8 November 2024; Accepted 9 November 2024

application of the solution since other relevant issues need to be faced. Examples are the consideration of such technology within the normative system or the issue of user acceptance. Regarding this last element, for a full use of a system by the user, he/she needs to rely on it with confidence, particularly if this system involves safety issues. It is therefore essential that the driver is aware of the potentialities of the system, relying on a clear man-machine interaction reporting information in an appropriate and timely manner. While driving in Truck Platooning, the driver in Follower position has a limited field of view and must surrender his authority to the Leader driver. This condition could affect the acceptance of this solution determining a stressful condition. The investigation of the level of stress during driving activity can be considered a useful indicator for considerations regarding the acceptance of the users towards this new system. Many studies assessed the level of stress of drivers during road test (Healey and Picard, 2005; De Nadai et al., 2016; Studer et al., 2018; Rodrigues et al., 2015). Concerning manual driving, numerous experiences were conducted on the road, while the behavior of the driver experimenting the automatic driving was mainly tested using driving simulators (Heikoop et al., 2017; Nakamura et al., 2010; Zheng et al., 2015).

This paper investigates the level of stress of the drivers during a real driving session in Truck Platooning, considering the reactions of the drivers to different situations that may occur while driving with reduced inter-vehicle distance. Similar research was developed in simulating environment. According to bibliographic research (Agriesti et al., 2018) it can be observed that the driver perceives a feeling of uncomfortable when the inter-vehicle distance decreases below 17 m. As concern test by simulator (Zheng et al., 2015), the first result regards the increase of the level of stress as a consequence to the decrease of the inter-vehicle distance, especially in a variable driving state. Then most of the participants experienced a feeling of unsafe when the preceding vehicle brakes (Nakamura et al., 2010). The aim of the paper is to provide further indications in this field of research, adding outcomes and results obtained by tests in real driving activities on the roads.

Research Gap: While many studies have examined the safety and efficiency of Truck Platooning, most of the existing research has relied on driving simulators to assess drivers' behavior, stress, and emotional responses in automated driving scenarios (Heikoop et al., 2017; Nakamura et al., 2010; Zheng et al., 2015). However, there is a lack of empirical studies conducted in real-world driving conditions that explore how truck platooning impacts drivers' psychophysical states. Simulation-based studies, though useful, may not fully capture the stress and cognitive workload drivers experience in real traffic situations, where unforeseen variables and environmental factors play a critical role (Agriesti et al., 2018; McDuff et al., 2014).

Study Contribution: This study addresses this gap by providing data from real on-road tests carried out as part of the European C-Roads project. Unlike previous research relying on simulated environments, this paper investigates the psychophysical state of drivers during actual Truck Platooning operations, using commercially available wearable devices to monitor physiological parameters such as Heart Rate Variability (HRV) and the Low Frequency/High Frequency (LF/HF) ratio, which is closely linked to stress levels (Agriesti et al., 2018; McDuff et al., 2014). The use of wearable smartwatches in a naturalistic setting allows for real-time monitoring of drivers' responses to various platooning conditions.

Significance of the Study: Understanding the stress levels of drivers engaged in Truck Platooning is critical for enhancing both the safety and user acceptance of this technology. Elevated stress levels can impair the driver's ability to react effectively in emergencies, especially in the role of the Follower, where direct control and visibility are limited. The findings of this study provide key insights for optimizing human-machine interaction in Truck Platooning systems, which is crucial for ensuring drivers' confidence and comfort. Moreover, by employing affordable and accessible wearable devices, this methodology is replicable and applicable to future studies involving stress analysis in other forms of assisted or automated driving scenarios.

2. State of the art

2.1. State of the art of Truck Platooning and driver behavior assessment

Several Truck Platooning studies have focused on the behavioral response of drivers, particularly in terms of stress and workload during platooning operations. The results indicate a range of stress-inducing factors, especially for Follower drivers, due to reduced visibility and inter-vehicle distances.

2.1.1. EDDI project (Germany)

The EDDI project found that drivers in the Follower position experienced elevated stress due to the short inter-vehicle distance and lack of control. Friedrichs et al. demonstrated that the use of effective Human-Machine Interfaces (HMIs) can mitigate stress by improving driver awareness and engagement in platooning (Friedrichs et al., 2016). The study underlined that cognitive load is significantly reduced when drivers have clear and intuitive interfaces that provide real-time information.

2.1.2. SARTRE project (Europe)

In the SARTRE project, drivers initially felt anxious due to unfamiliarity with close-following distances. However, Hjälmdahl et al. showed that over time, stress levels decreased as drivers adapted to the platooning dynamics, especially when safety features like Cooperative Adaptive Cruise Control (CACC) were trusted (Hjälmdahl et al., 2017). The study concluded that driver adaptation is key to reducing anxiety in semi-automated driving scenarios.

2.1.3. ENSEMBLE project (Europe)

The ENSEMBLE project aimed to integrate multi-brand platooning systems. Initial findings from Fröhlich et al. demonstrated that during platoon formation and disengagement, drivers in the Follower position reported higher stress, particularly when they experienced sudden braking or acceleration (Fröhlich et al., 2018). This research emphasized the importance of stress management systems and continuous driver feedback to ensure smoother transitions between manual and automated control.

2.1.4. Connecting Austria project

Connecting Austria project highlighted the challenges in driver acceptance of platooning. It found that driver stress was primarily related to the unpredictability of traffic events and system reliability during platooning phases. Connecting Austria recommended adaptive driver assistance systems that monitor both external traffic conditions and driver stress levels to better support Follower drivers and enhance overall system acceptance (Schildorfer et al., 2020). It was emphasized the importance of real-time feedback to drivers to reduce uncertainty during platooning operations.

2.1.5. Additional findings

Studies like Zheng et al. have shown that effective human-machine interaction systems can reduce cognitive workload by offering clear visual and auditory signals to drivers during platooning (Zheng et al., 2013). Engström et al. further noted that the implementation of semi-autonomous driving requires detailed user training, as unprepared drivers can experience higher stress levels when faced with unpredictable situations like cut-ins or sudden deceleration (Engström et al., 2018).

2.2. State of the art on driver psychophysiological state detection using HRV (HF and LF analysis)

Heart Rate Variability (HRV) has proven to be a powerful tool for assessing drivers' psychophysiological state, especially in stressful driving scenarios like Truck Platooning. By analyzing Low Frequency (LF) and High Frequency (HF) components, researchers can infer the balance between the Sympathetic Nervous System (SNS) and the Parasympathetic Nervous System (PNS), which is critical for understanding stress and mental workload (Shaffer and Ginsberg, 2017).

2.2.1. HRV as a stress indicator

HRV captures fluctuations in autonomic nervous system activity. The LF band is associated with sympathetic activity, while the HF band is linked to parasympathetic activity, particularly during relaxed states (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). The LF/HF ratio is frequently used as an index of autonomic balance, with a higher ratio indicating stress (McDuff et al., 2014).

2.2.2. HRV and driving stress

Studies such as Healey and Picard have demonstrated the effectiveness of HRV as a real-time stress indicator during driving, showing that the LF/HF ratio increases in stressful conditions like traffic (Healey and Picard, 2005). De Nadai et al. applied HRV analysis to Truck Platooning, showing that reduced inter-vehicle distance correlates with increased stress in Follower drivers, particularly during platoon engagement and disengagement phases (De Nadai et al., 2016). Friedrichs et al. also found that semi-automated systems can induce stress in drivers, especially those unfamiliar with the technology (Friedrichs et al., 2016).

2.2.3. HRV measurement techniques

The most reliable method for HRV measurement is through electrocardiography (ECG), but wearable devices have gained popularity for continuous, non-invasive monitoring in real-world settings. These devices allow real-time capture of physiological data such as HRV, making them suitable for tracking stress in dynamic environments like driving (McDuff et al., 2014). Using frequency domain analysis such as Fast Fourier Transform (FFT), HRV data can be converted into LF and HF power spectral densities, offering insights into drivers' stress levels (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996).

2.2.4. Applications in automated driving

The use of HRV in assessing driver stress has significant implications for semi-automated driving systems, including Truck Platooning. Studies by Hjälmdahl et al. show that drivers initially experience higher stress due to the unfamiliarity with automated systems, although stress levels tend to decrease as trust in the technology grows (Hjälmdahl et al., 2017). Similarly, Zheng et al. demonstrated that providing drivers with real-time physiological feedback (including HRV data) helped them manage stress during platooning tasks (Zheng et al., 2013).

2.2.5. Future directions

While HRV remains a valuable method for stress monitoring, challenges persist, particularly regarding the accuracy of wearable devices compared to medical-grade ECGs (Shaffer and Ginsberg, 2017). Future research could focus on integrating HRV with other physiological indicators such as skin conductance or eye tracking to provide a more comprehensive understanding of driver stress. Additionally, machine learning algorithms could be employed to personalize stress models, enabling automated driving systems to adapt to individual drivers' physiological responses, improving both safety and comfort.

Table 1
Symbols and metrics.

Metric	Description	Unit
HRV (Heart Rate Variability)	Variability in time intervals between heartbeats, used to assess stress levels	Milliseconds
LF (Low Frequency)	Power of low-frequency HRV component, linked to sympathetic activity	Hertz (Hz)
HF (High Frequency)	Power of high-frequency HRV component, associated with parasympathetic activity	Hertz (Hz)
LF/HF Ratio	Ratio of LF to HF components, used as an indicator of stress	Dimensionless
Stress Index	Indicator derived from physiological data to measure stress level	Index
t	Time during the platooning experiment	sec

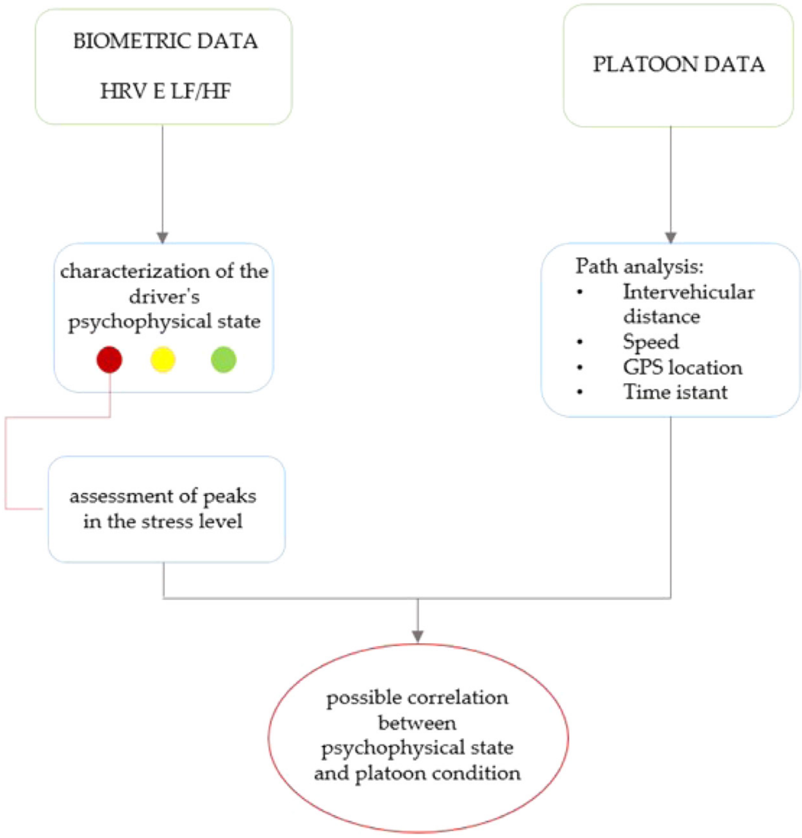

Fig. 1. Schematic description of the adopted procedure.

3. Methodological approach

Table 1 resumes for an easier understanding the symbols and metrics adopted in the text.

From the methodological point of view, the approach adopted in the present study can be summarized by the diagram reported in Fig. 1.

The procedure is based on the elaboration of data collected during the driving tests on roads. This data collection would made possible the investigation of the correlations between the driver's psychophysical condition and the different states of the platoon. The results, thanks to an increased knowledge of the status of the drivers, could allow further optimization of the system towards an improved user acceptance.

The first set of data collected is represented by the biometric data. Particularly, the HRV (Heart Rate Variability) was selected as the representative physiological parameter, since the scientific literature (McDuff et al., 2014) underlines that the heart frequency promptly reacts to the personal emotions, such as anxiety or relaxation. The processing of the heart frequency, and particularly the parameter LF/HF (Low Frequency/High Frequency), provides the characterization of the driver's psychophysical state and consequently the identification of the peaks in the stress level during the road tests.

This first data set is integrated with the data coming from the trucks regarding the platoon and more generally the driving activity. A wide set of data can be collected and analyzed such as the inter-vehicle distance, the GPS localization, the event featuring the status

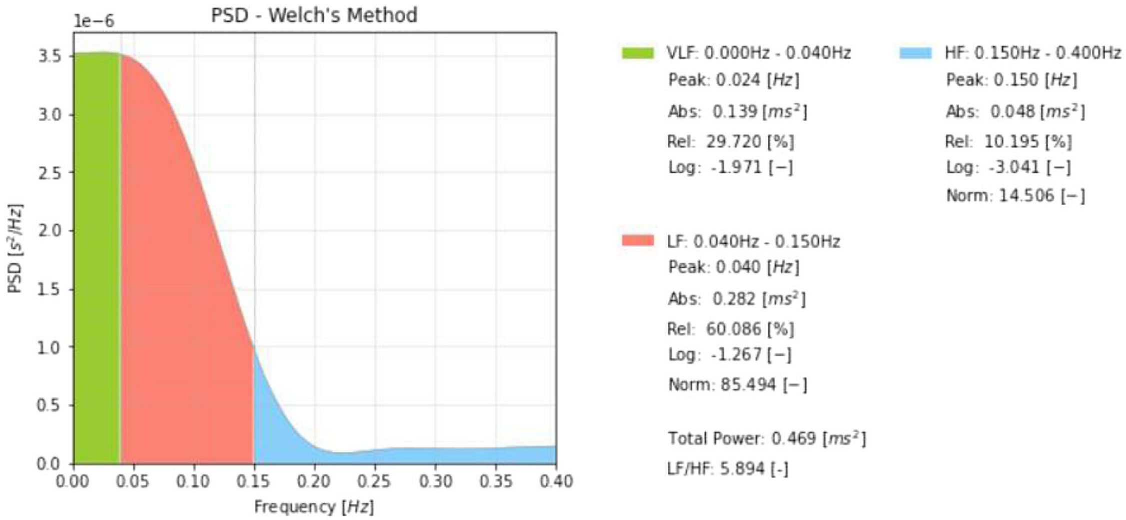

Fig. 2. Power Spectral Density (PSD) in case of stressful situation – High LF/HF ratio.

of the platooning, the speed and the acceleration, etc. All these information are also detailed with a temporal indication, with a time step of 0,25 s.

A double correlation, both spatial and temporal, is conducted between the two data sets with the aim of investigating the most stressing situation for the drivers and if differences in their behavior in different positions (Leader and Follower) exist.

3.1. Physiological parameter

The study by McDuff et al. (2014) illustrates that the parameter LF/HF can identify the mental workload to which a person is subjected, for example performing algebraic operations. In a similar way in the study carried out by De Nadai et al. (2016) the same parameter was used to investigate the driver's stress level. In the present study, the ratio LF/HF is obtained from the elaboration of the heart frequency and its variability (HRV – Heart Rate Variability); the ratio is then used to feature the driver's psychophysical state and the peaks of the stress level (i.e. level of stress identified as "high") during the tests on road.

The Heart Rate Variability is a measure connected to the activity of the Automatic Nervous System (ANS) (Studer et al., 2019). It is responsible of the regulation of the activities of the organs regardless of the will of the individual. The ANS is subdivided in two branches: the Sympathetic Nervous System (SNS), that acts during emergency situations and occurs with tachycardia and increased pressure, and the Parasympathetic Nervous System (PNS), that acts during rest moments and occurs with slow heart rate and low blood pressure. The parameter LF/HF represents the relationship between low frequencies and high frequencies. Thus, it is featuring the relationship between the SNS and the PNS. In particular, the PNS activities are characterized from the HF band's power spectral, while the ANS ones are characterized from the LF band.

The frequency values to assess the bands are:

- Low Frequency band: 0.04 – 0.15 HZ
- High Frequency band: 0.15 – 0.40 HZ

During a stressful event, a greater value in the LF/HF parameter is recorded (McDuff et al., 2014): in the Fig. 2, the low frequencies are prevailing and the ratio LF/HF is equal to 5.894. On the contrary in a relaxing situation the high frequencies are prevailing and a value equal to is obtained 0.103, as reported in Fig. 3.

3.2. Platoon data

For the purposes of the research the main elements to be considered to feature the Truck Platoon are the vehicle's GPS position, its velocity and acceleration, the distance between vehicles, the number of vehicles involved in the platoon, the information concerning the different phases of driving in platoon: engagement, steady state, disengagement.

The data referred to Truck Platooning can be directly recorded by the trucks during the field tests, and then collected and analyzed. This allows to describe in detail the driving behavior and the status of the platoon over time. Examples of data are reported in the following figures. Fig. 4 illustrates the number of vehicles joining the platoon over time. Fig. 5 reports the status of the platoon according to the coding adopted by IVECO, where the code "11", maximum value recordable, stands for the condition of "Steady State" platoon. Other observable codes are "10", reflecting a temporary switch off of the system, "1" i.e. system ON, "7" i.e. engaging and "8" i.e. disengaging. Fig. 6 and Fig. 7 show the instantaneous speed of the vehicle and its distance by the preceding vehicle (i.e. the leader).

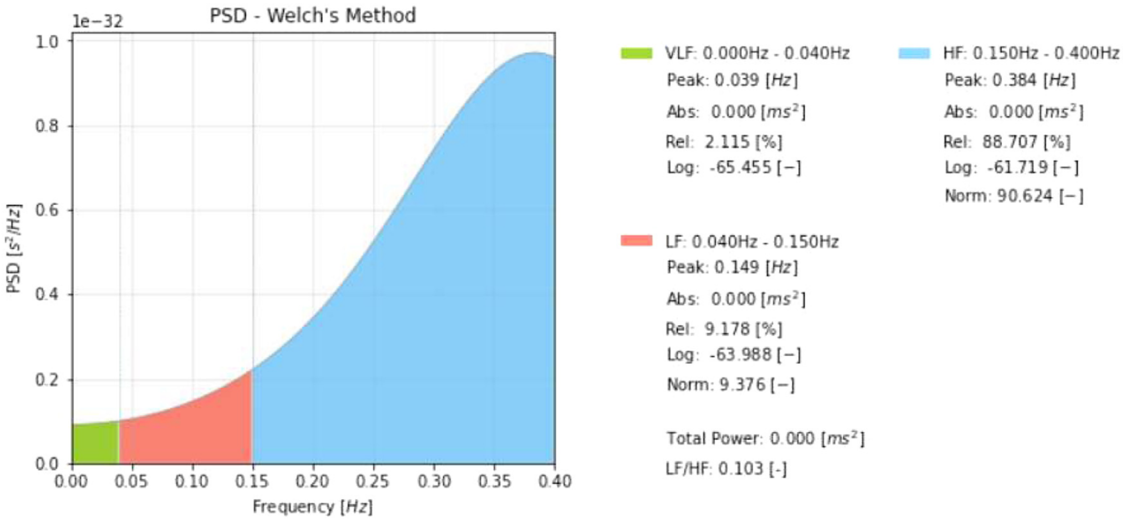

Fig. 3. Power Spectral Density (PSD) in case of relaxing situation – Low LF/HF ratio.

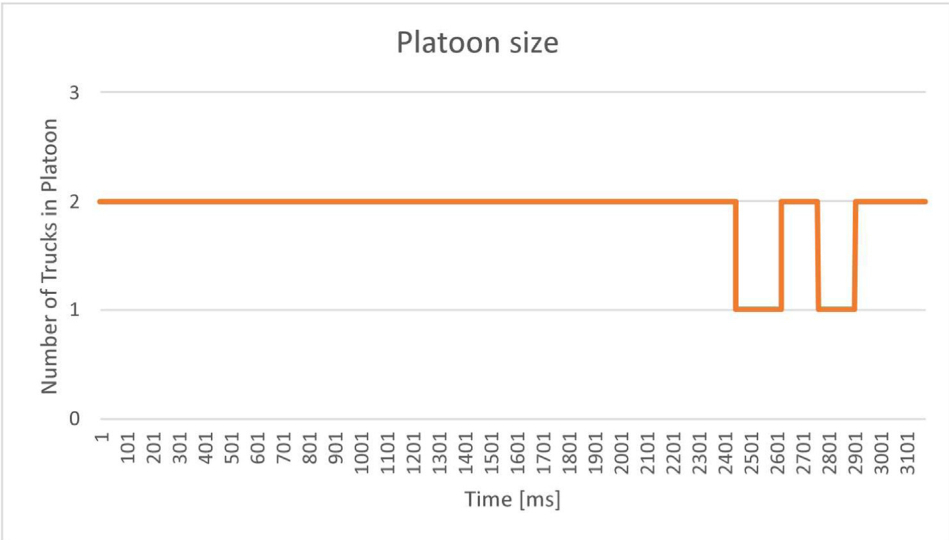

Fig. 4. Number of vehicles joining the platoon over time.

These images report an example of transition from a stable platoon to an unstable platoon condition. This instability also features the variables that are influenced by platooning phases such as intravehicular distance and speed. Since the platoon is stable (i.e. the first time interval) the inter-vehicle distance is almost constant around 30 m and also the instantaneous speed is stable around 84 km/h. This condition results in reduced accelerations/decelerations with recognized positive impacts on traffic efficiency and environment.

3.3. Field tests on road - Data collection and analysis

Field tests on road allowed an extended data collection activity. These field tests relied on the European Project C-Roads (www.c-roads.eu/platform.html), part of the Connected European Facility program. The Project involves tests of the Truck Platooning technology on the Italian motorways Autostrada del Brennero S.p.A., Concessioni Autostradali Venete S.p.A. and Autostrade Alto Adriatico S.p.A. (previous Autovie Venete S.p.A.). The truck manufacturer company IVECO S.p.A. provided the trucks allowing the deployment of Truck Platooning.

The test campaign was carried out engaging 2 male professional drivers, already driving in platoon during the C-Roads Project's field tests. Driving activity was performed throughout daytime in a non-controlled environment. Drivers faced then different conditions, with levels of traffic flows ranging from medium to high, as usual during this time of the day along the Brennero Motorway.

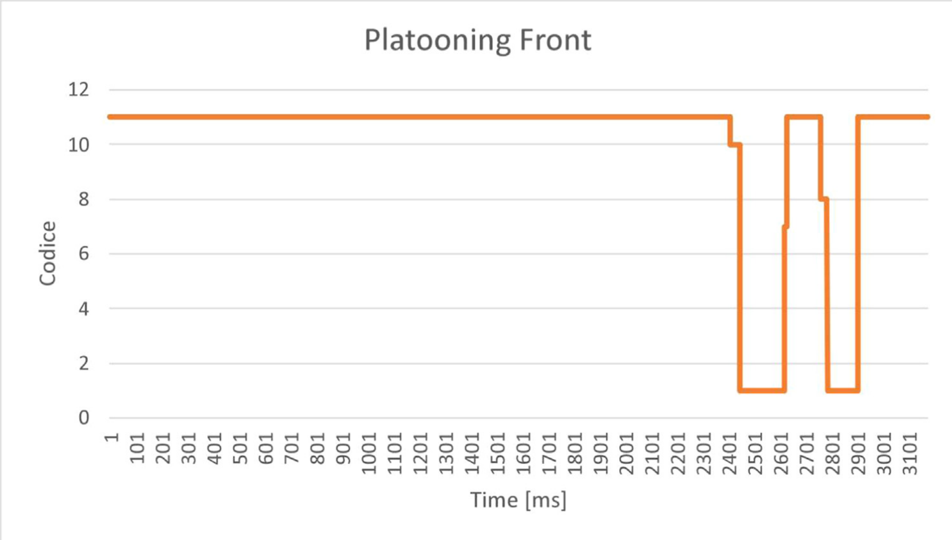

Fig. 5. Codes defining the condition of the vehicle in the different phases of platoon over time, as recorded by the follower vehicle.

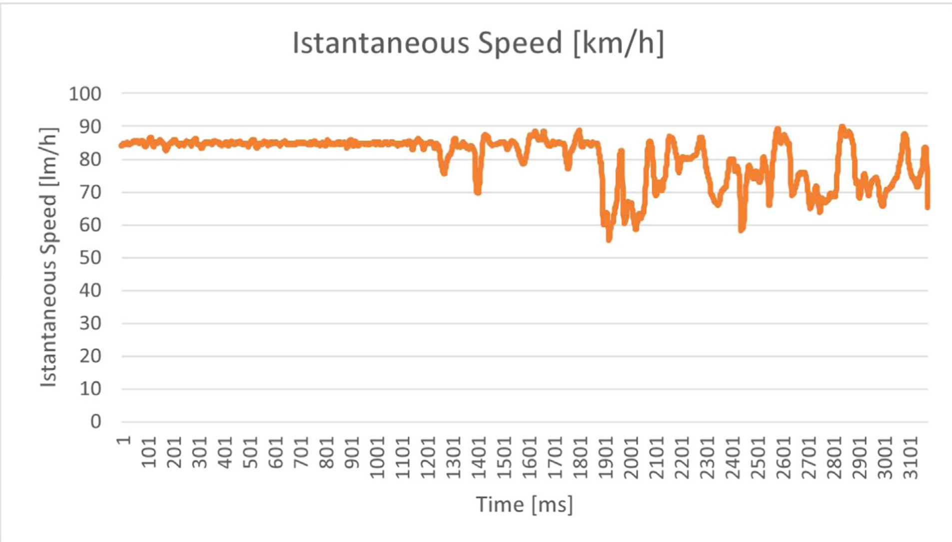

Fig. 6. Speed of the vehicle over time.

Physiological parameters were collected adopting the smartwatch Xiaomi Mi Band 5: they allow to record the heart frequency with a predetermined sampling interval. This device has already been used to investigate the stress in the workplace and the results obtained during the validation phase with manual guide test appeared reliable. It is a device that can be easily used by non-experts, with no need of relevant training, accessible from an economic point of view and easily controllable, even remotely, in case of request of assistance by the drivers involved. These were considered key features for the monitoring of actual drivers in real and extended driving condition in a not-controlled environment.

The experimentation activity required a start-up moment. On the IVECO premises in Trento, the coupling operations between the smartwatches adopted to collect physiological parameter and the trucks were held and the formalities about the data processing, according to the UE regulation (n.679/2016 – Art.13) were carried out.

During the start-up event, the Mi Fit and Tools & Mi Band applications were installed on the tablets already present on the trucks and then pair to the devices (Fig. 8).

After briefly training the drivers about the procedures to export and share the data collected, during the following test days the driver only have to wear the bracelet, without activate any monitoring or take care of additional tasks.

Applications allow to export .csv files, that are the basis for LF/HF parameter's analysis. In particular, the RR parameter is obtained from the processing of the heart rate recording. The RR represents the input of the Python code adopted for the data elaborations.

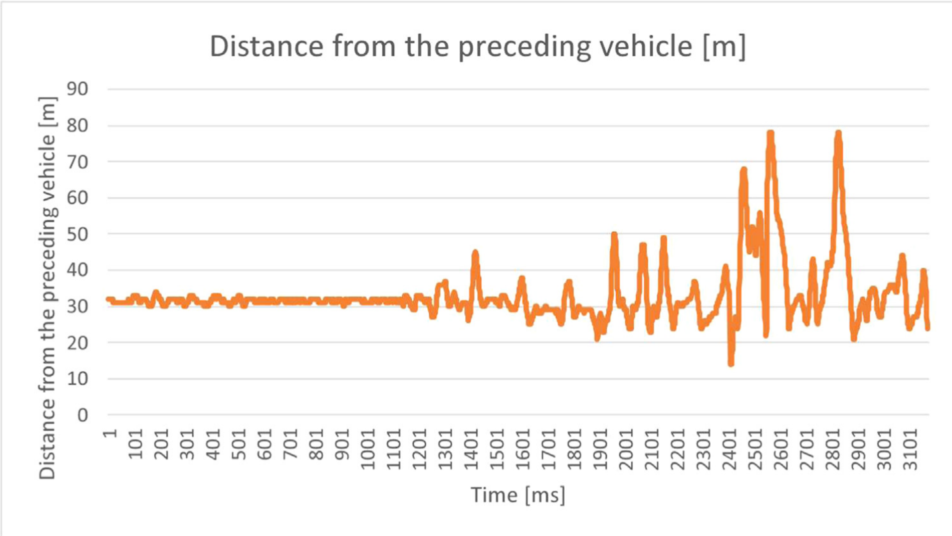

Fig. 7. Distance between vehicles over time.

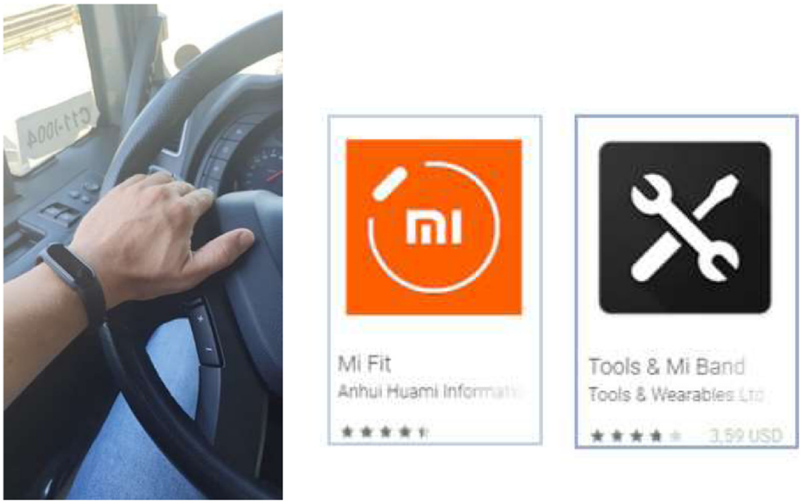

Fig. 8. Applications adopted for the test activity.

From the Section 2.4 "Frequency Domain Module" of the library available at https://pyhrv.readthedocs.io/en/latest/, the “fft_ratio” function was chosen in order to evaluate the LF/HF ratio on a 10-second basis.

Tests on road were developed relying on the trips carried out during the C-Roads European project. In particular, the tests of Truck Platooning technology performed by IVECO on the Brenner motorway A22 were considered (Fig. 9). The journeys were conducted from June 23rd to July 9th, 2021, using two vehicles simultaneously, for a total of 108 h of recordings.

It was possible to support the driver during a sample journey in Truck Platooning from Trento and Rovereto. This allowed a direct confrontation with the drivers, obtaining information about their sensations and feelings, so to perform a brief qualitative investigation of the topic. In both positions of Follower and Leader in the Platoon, the drivers reported in the interviews to feel at ease and not worried or threatened by the reduced control of the vehicle.

For each test day, a calibration was carried out for both drivers considering 10 min at rest before departure. Thresholds for three conditions of stress were then defined, based on the average LF/HF ratio recorded (x_m) and its standard deviation (σ).

High stress level

$$\left(\frac{LF}{HF}\right)_i \geq x_m + \sigma$$

Medium stress level

$$x_m - \sigma < \left(\frac{LF}{HF}\right)_i < x_m + \sigma$$

Fig. 9. IVECO trucks used for the tests.

Fig. 10. Samples maps reporting the stress level and the platoon condition. Direction from north to south.

Low stress level, associated with a state of relaxation

$$\left(\frac{LF}{HF}\right)_i \leq x_m - \sigma$$

The information about the level of stress while driving was reported in a map using the opensource QGIS software and adopting a set of colors, to allow a faster and more intuitive interpretation.

In parallel, the condition of the platoon was also represented using a dot whose color gradation indicates the different distance between the vehicles: a darker color indicates a smaller inter-vehicle distance. The correlation between the two groups of data was then performed (Fig. 10).

3.4. Limitations of statistical analysis

In our study, the use of statistical methods like correlation analysis (e.g., Pearson and Spearman) and hypothesis testing (e.g., *t*-tests) is limited due to the specific conditions of our data. Firstly, the sample size is relatively small, and the real-world driving environment introduces a lot of variability - factors like traffic, weather, and road conditions add noise to our data. This makes it difficult to meet certain assumptions, such as the normal distribution and consistency of variance, that are required for reliable use of techniques like the Pearson correlation or *t*-tests. Additionally, Truck Platooning involves multiple interacting factors (e.g., platoon phases, inter-vehicle distance, driver roles) that are hard to isolate in real-world conditions. The continuous, real-time data collection also means that many data points are not independent, further limiting the use of traditional statistical tests, which assume independent samples. Given these limitations, we chose an exploratory and descriptive approach to analyze the data. While this means we cannot draw definitive statistical conclusions, it allows us to better reflect the complex and variable nature of real-world Truck Platooning scenarios.

For future studies, we recommend larger datasets and controlled environments to allow for more robust statistical analysis.

3.5. Comments to the methodology

The objective of this study is to define and test a rapid methodology to investigate drivers' stress levels during Truck Platooning, rather than evaluate the user acceptance of the platooning service itself, which has already been thoroughly tested by

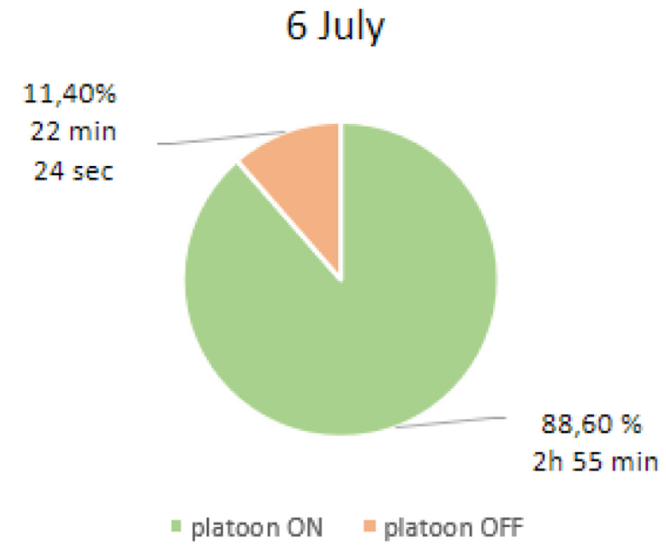

Fig. 11. Time spent in platoon and in manual driving. Sample of test on 6th July.

IVECO. By using wearable devices and analyzing physiological parameters such as Heart Rate Variability (HRV), this study aims to provide a replicable, low-cost method to monitor real-time stress reactions, particularly during challenging driving conditions. This approach focuses on the practical assessment of stress indicators, offering insights into how drivers cope with platooning environments.

This study's core objective was not to gather qualitative feedback through structured interviews but to develop and test an objective, real-time stress monitoring methodology. Using wearable devices to track physiological parameters (such as HRV and LF/HF ratio), we sought to investigate drivers' stress levels during different phases of Truck Platooning. Although informal driver feedback was collected, it served as supplementary information and not as a primary data collection method. Therefore, formal interview guidelines and subjective frameworks were not necessary for the goals of this research. The focus remained on providing a replicable and efficient methodology for assessing driver stress in real-world conditions.

4. Results

The analysis of the correlation was developed trying to find answers to two main research questions:

Is the driver's psychophysical state affected by driving in platoon?

In which situations a high level of stress is recorded in the driver of the Follower vehicle?

4.1. Is the driver's psychophysical state affected by driving in platoon?

To answer this question, a normalization of the stress levels recorded over time was required, to allow a meaningful benchmarking between the condition with platoon engaged versus disengaged. Indeed, during the driving activity, the time spent in platoon is much higher than in manual driving, witnessing an overall reliability of the system (Fig. 11).

The reference adopted indicator was the following ratio:

$$\frac{\textit{NUMBER OF EVENTS WITH HIGH STRESS}}{\textit{TIME}}$$

Moreover, the analysis was carried out just on referring to the mileage on highways, excluding those on exits and entrances (i.e. links of the junctions), where high level of stress were typically recorded in a condition of platoon disengaged (Fig. 12).

The graphs (Fig. 13 and 14) show how the recorded number of stressful events was lower for both the leading and following drivers while driving in platoon.

The comparison is particularly relevant for the follower driver, since the leader was not experiencing in platoon a different activity compared to the traditional driving. Data about the follower witness that he was driving in a more relaxed way, with a reduction of the number of events featured by high stress over time by 27 %. This maximum decrease was observed during the last day of test, that could be motivated by a progressive growth of the confidence level towards the system.

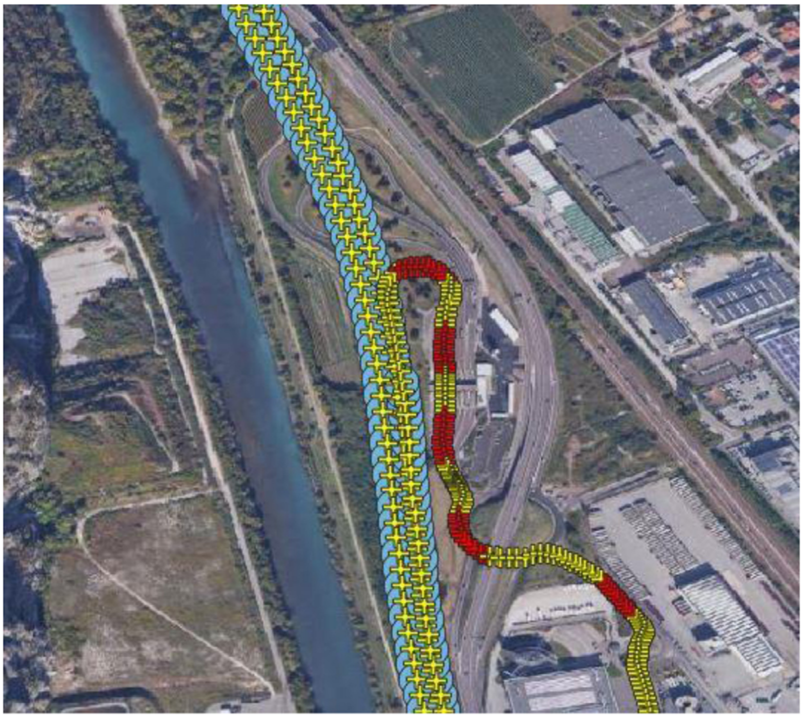

Fig. 12. High stress (red crosses) recorded in junctions. Sample of test on 6th July.

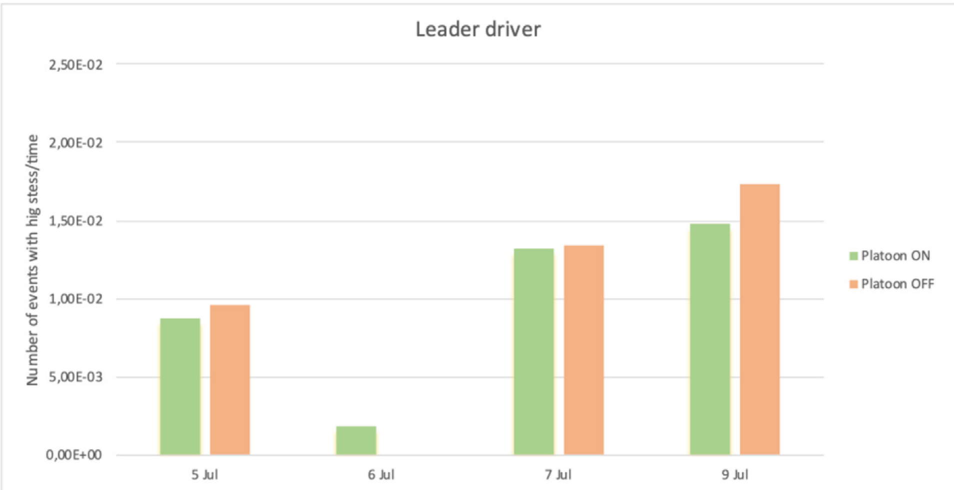

Fig. 13. Number of recorded events with high stress over time for the leader driver.

4.2. Which situations can determine a high level of stress in the follower driver?

A deeper analysis on the follower driver was carried out to investigate single stressful conditions for this subject.

The whole set of events featured by high level of stress level for the follower driver was analyzed. These, whenever possible, were then clustered into a set of representative circumstances that could a sense of nervousness or uncertainty in the driver:

- Inter-vehicle distance variation
- Singular points of the roadway: bridge, underpasses or marked curves
- Junction: presence of the deceleration/acceleration lanes.

Fig. 14. Number of recorded events with high stress over time for the follower driver.

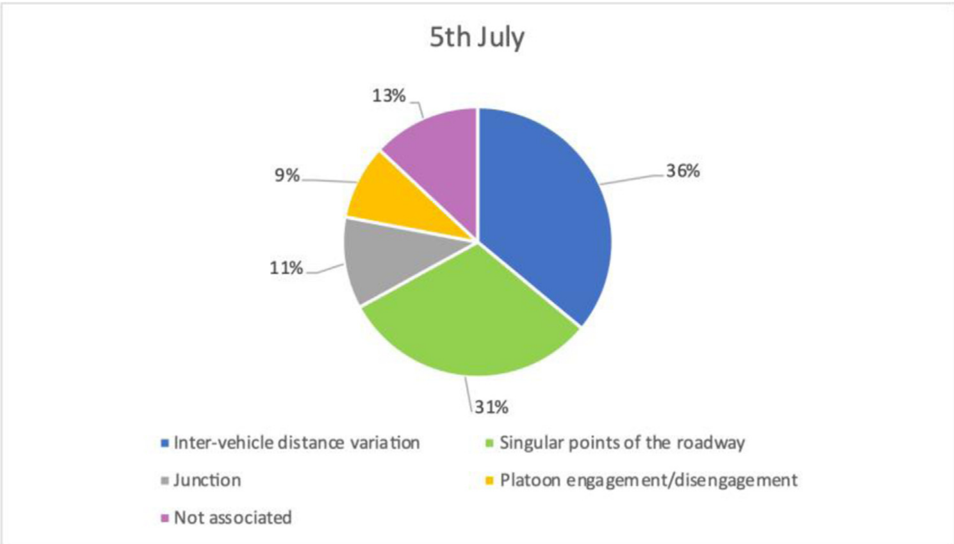

Fig. 15. Distribution of events with high level of stress for the follower driver over the circumstances – 5th July.

- Platoon engagement/disengagement maneuvers.

A high level of stress is linked to one of these four circumstances in most of the cases. Indeed, considering two meaningful sample days (i.e. featured by a relevant number of stressful events, 5th and 6th of July 2021), this association was possible in the 87 % and 82 % of cases respectively (see Fig. 15 and Fig. 16).

The data collected allowed the deep analysis concerning the relation between stress levels and platoon for specific situations or locations along the highway. As example, the following cases are reported:

- Motorway junctions;
- Cut-in maneuvers;
- Platoon engagement/disengagement maneuvers.

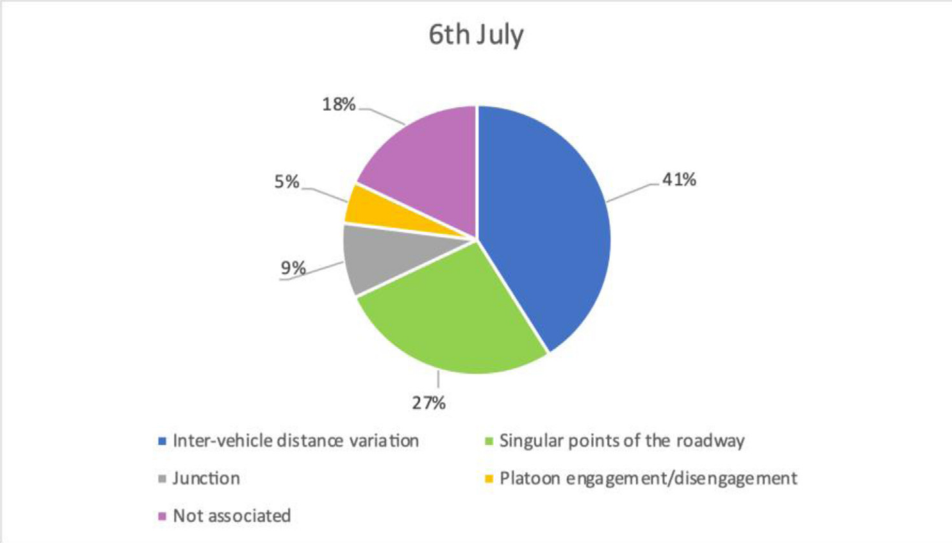

Fig. 16. Distribution of events with high level of stress for the follower driver over the circumstances – 6th July.

Fig. 17. Leader vehicle, medium stress level nearby a sample motorway junction.

4.2.1. *Motorway junctions*

Fig. 17 and Fig. 18 show the recorded stress levels nearby a sample junction for the leader and the follower driver respectively, overlapped with the information about the inter-vehicle distance.

The leader driver was featured by a low or medium stress level, whatever was the direction considered (Fig. 17). On the contrary the follower driver felt a high level of stress in both directions, regardless of the inter-vehicle distance, mainly when sided by the deceleration lane, then before the junction itself (Fig. 18). Among the possible causes it can be considered the uncertainty of the maneuvers that the leader driver could carry out but also the fear of the sudden insertion of an external vehicle between the two vehicles in platoon (cut-in maneuver), situation that actually occurred during the test days.

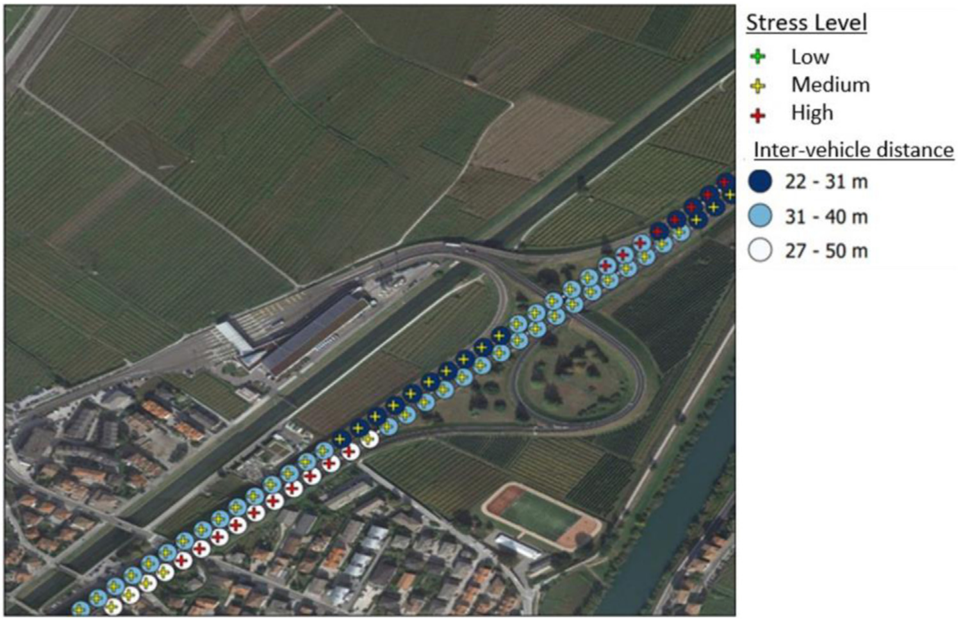

Fig. 18. Follower vehicle, high stress level nearby a sample motorway junction.

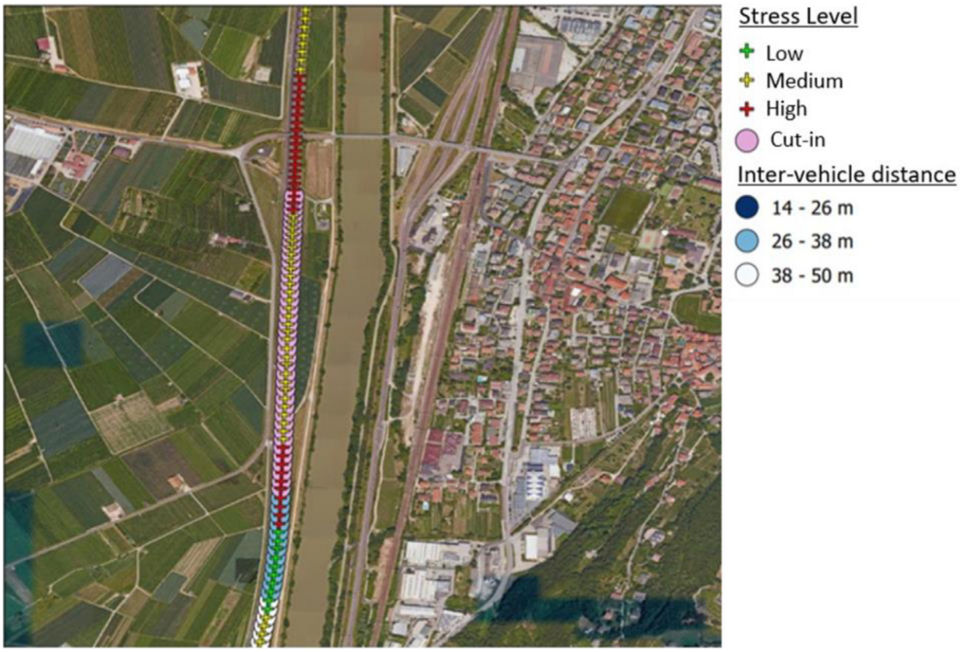

Fig. 19. Follower vehicle, high stress level recorded due to a cut-in maneuver.

4.2.2. Cut-in maneuvers

During the recorded cut-in maneuvers, two peaks in the stress level of the follower driver were usually detected. The first one can be linked to the actual insertion of the vehicle, with its dynamic consequences, while the second can be related to the disaggregation of the platoon itself. Fig. 19 reports a sample case of a cut-in maneuver for a platoon travelling from south to north. The different phases leading to the disengagement of the platoon can be observed, with the sequence of stress level described: a first time interval featured by high stress, as the cut-in started, and a second one detected when the platoon is dissolved (red cross with no circle in Fig. 19).

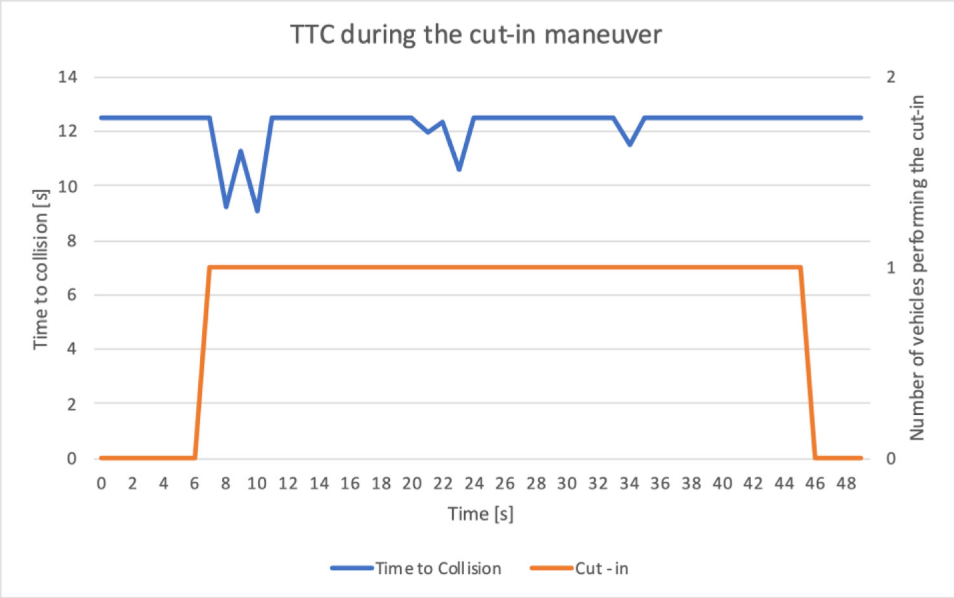

Fig. 20. TTC during the cut-in maneuver.

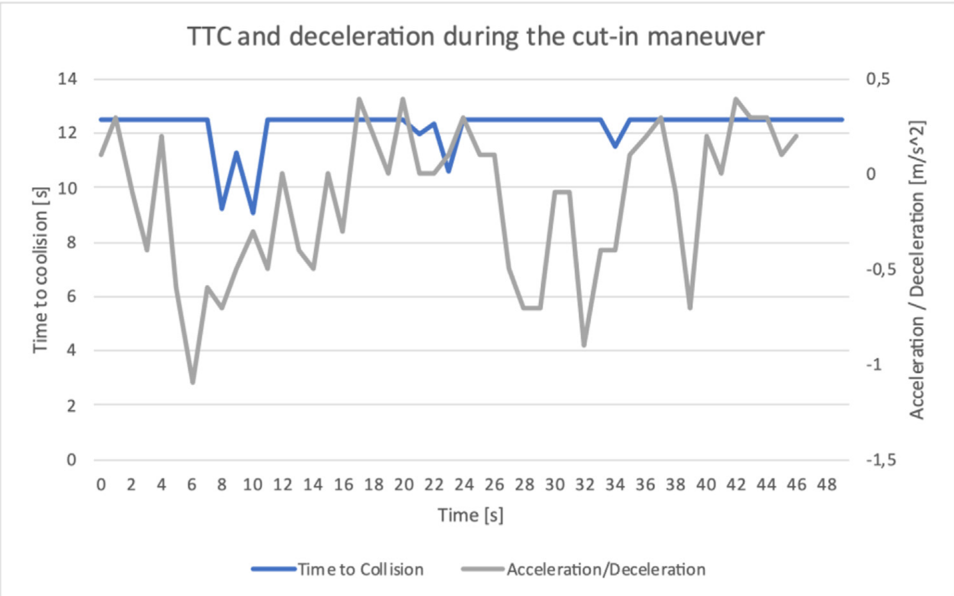

Fig. 21. TTC and acceleration/deceleration during the cut-in maneuver.

To further characterize these situations, the elaboration of the parameter Time to Collision (TTC) was developed, joined with the analysis of the recorded decelerations. In the example considered, the log file of the truck follower highlighted a decrease in the TTC from 12.5 to 9 s (in blue in the Fig. 20).

At the same time a relevant deceleration greater than 1 m/s^2 (in grey in Fig. 21) was also recorded, witnessing a perceived risky situation.

4.2.3. Platoon engaging and disengaging maneuvers

As other circumstances, the maneuvers of platoon engaging and disengaging determined higher level of stress in the follower driver rather than in the leader one. The whole set of data collected and its analysis allowed to quantify this gap: a high level of stress

Fig. 22. Follower vehicle, high stress level during the platoon engaging/disengaging.

was observed in 80 % of these maneuvers for the follower driver, while this condition featured only the 44 % of the cases for the leader.

The Fig. 22 reports examples of the correlation between the platoon state and the high stress level recorded for the follower driver. A particular situation is reported in the image 2 of Fig. 22, showing the detection of a high level of stress at the tunnel. This singular point, leading to the disengagement of the platoon, determined a constant high level of stress for both drivers during all the tests.

5. Conclusions

The activities described allowed the design of an experimental protocol intended to detect and elaborate data for the analysis of a driver's stress level, to be applied to the driving activity with Truck Platooning. The goal was to design a method with features of replicability, economically affordable and based on opensource software and applications. Although the device used (Xiaomi Mi Band 5) is less accurate than a medical instrumentation with a high level of reliability, it can be concluded that the method, based on the elaboration of the LF/HF ratio, can be considered consistent. Indeed, it allowed the monitoring of level of stress all over the driving activity with reliable results.

Two research questions drove the application of the method:

- Is the driver's psychophysical state affected by driving in platoon?
- In which situations a high level of stress is recorded in the driver of the Follower vehicle?

Concerning the first question, the application of the protocol showed that the recorded number of stressful events was lower for both the leading and following drivers while driving in platoon. Referring also to the phases of engagement and disengagement, the monitoring of the Follower driver, compared to the Leader, showed globally a higher level of stress. This represented an expected result, but the experimental activity allowed the quantification of this condition.

The comparison was particularly relevant for the follower driver, since the leader was not experiencing in platoon a different activity compared to the traditional driving.

The data presented in this study indicates that Leader drivers did not exhibit significant stress during Truck Platooning. This can be attributed to the fact that the drivers involved had already accumulated over 300,000 km of platooning experience during the C-Roads project. Their familiarity with the system likely reduced the stress typically associated with the Leader's responsibility. While other research, such as the EDDI project, suggests that Leader drivers may feel stress, in our case, the extensive experience mitigated this effect.

Data about the follower witnessed that he was driving in a more relaxed way, with a reduction of the number of events featured by high stress over time by 27 %. This maximum decrease was observed during the last day of test, as a result of a progressive growth in the confidence level towards the system.

About the second research question, the high level of stress was detected in association with punctual circumstances. In particular, it was possible to link around the 85 % of high stress conditions to a cluster of four peculiar situations:

- Inter-vehicle distance variation (around 39 %);
- Singular points of the roadway: bridge, underpasses or marked curves (around 29 %);
- Junction: presence of the deceleration/acceleration lanes (around 10 %);
- Platoon engagement/disengagement maneuvers (around 7 %).

A deeper investigation on samples of these situations allowed to recognize common and replicated relations and evolutions between recorded stress levels and driving activity.

The partial ease in the actual deployment of the tests and the limited costs grant the replicability of the approach to further applications in the field of innovative solutions for transports. Among them, the investigation of the impacts of C-ITS on the drivers should be mentioned. Indeed, this technology was available on the IVECO trucks used for the tests and preliminary analysis were carried out.

Funding

This research received no external funding.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *Multimodal Transportation* and was not involved in the editorial review or the decision to publish this article.

CRediT authorship contribution statement

Paolo Gandini: Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Luca Studer:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Marta Zecchini:** Writing – original draft, Software, Formal analysis, Data curation. **Marco Ponti:** Writing – review & editing, Validation, Formal analysis.

Acknowledgement

We thank Eng. Valerio Liga, from IVECO Group, for his assistance in the preparation, in the deployment of the field tests and for providing the trucks.

We would also like to show our gratitude to the Professor Paolo Perego and Giuseppe Andreoni, from Technology and Design for Healthcare Laboratory—Politecnico di Milano, Design Dep., for their valuable contribution in the psychophysical data specification and analysis.

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