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Towards cooperative management of fatigue and vigilance in railway operations

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Abstract. Professional drivers face fatigue and decrease of vigilance over the long driving sessions paving their everyday life. This naturally occurring phenomenon is acknowledged and preventive measures, adapted to the vehicles and missions, are deployed around the world to limit the related risks. As technology opened the way to affordable probing of human bio-signals and activities, more active strategies are investigated such as sleepiness monitoring and alert systems. Such systems already existed in trains, although in a more primitive form, known as "dead-man switch". As the limitations of this system in detecting actual vigilance decrements is known from practitioners, we took upon ourselves to explore the opportunities offered by the recent developments, under the strict security constraint that characterises railway operations. Going further than monitoring and alert, we consider the ideas of a bio-signal feedback loop and adaptive levels of automation to encourage a real cooperation between the driver and the system in managing fatigue and vigilance. This challenge is particularly significant in teleoperation, which emerges as a potential evolution of the railway activity where fatigue and vigilance are affected by information loss and increased reliance on visual information. Such cooperative work would pave the way for a new definition of what a train driver is, emphasizing its critical role of safeguarding the train and its passengers. This is especially important in a context of autonomous systems' proliferation, putting the drivers' position at risks.

1 Introduction

The issue of waning vigilance during sustained activities is globally acknowledged and a quantification of the decrements has been performed as early as 1948 [1]. This can be the cause of accidents in many situations, notably in industrial activities and transportation, where vigilance failures can potentially put lives at stake. It is especially important in the context of the train driving activity, which consists of sustained periods of driving that can often become quite monotonous, further increasing the risk of driver fatigue.

In railway transportation, the driver is perhaps the most important actor in ensuring the safety of passengers, the train and the infrastructure. In order to maintain the driver's vigilance at all times during the activity, active protection systems have been developed. These systems are able to interrupt circulation when the drivers fails to interact in time with them, such as when losing consciousness. In France, the system known as VACMA accomplishes that role [2], comparable to SIFA in Germany [3], and similar systems are usually mandatory for trains throughout Europe.

These drivers vigilance monitoring systems are welcome as a first security layer, but are also pointed out for their limited ability in detecting actual vigilance issue [2, 3]. This very limited capability owned them the title of '*dead-man switch*', underling the fact the system is mostly limited to the detection of critical situations.

This situation led to questionings on how to better assess vigilance during the activity. Hopefully, the academic literature is rich of works on the analysis of human states and behaviors, especially on the exploitation of quantifiable signals to perform trustworthy estimates. Recent developments have boomed in the automotive industry, offering new opportunities through commercially available hardware and robust processing algorithms. This led us to review the different possibilities applicable in the context of the French railways, as well as consider how such system could integrate in a cooperative driving activity including automated/autonomous systems.

2 Human activities and bio-signals

Following the recent development in drivers monitoring systems, multiples possible inputs emerge to follow drivers' activity. As such, it is important to consider these inputs in maters of strength and weakness, but also in maters of required systems to exploit them. A balance should be found between the quality of the detection and the usability in real conditions. Thus, commonly found inputs shall be presented now.

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2.1 Bio-signals reading & state estimation

Developments over the past decades consolidated knowledge on the relationship between humans' internal state and observable signals. Thanks to this consolidation, consumer applications are arising, especially for car drivers who now have access to sleepiness warning systems. Sleepiness warning systems mostly exploit facial feature or head tilt, which are quite explicit signs of ongoing sleepiness, to estimate the current state of the driver. While the current case is based on naturalistic observations, it exploit a larger concept: by analyzing available signals and behavior related to humans' internal states, it become possible to deduct internal states.

This analysis of internal state require, however, a good comprehension of signals related to the studied state and the possible interference, both in signal reading and state triggers. For example, cardiac features are strongly correlated to stressors, but does not imply that the stressors are necessarily related to the activity, nor that a negative observation imply the total absence of stressors in the activity. This explain why some works such as [4, 5] display the exploitation of multiples different signals to identify a single state ; through data comparison, it become easier to discriminate between states, either by taking into account multiple possible states, or through cross-validation of the targeted state.

Multiples states may be of interest in the design of a monitoring system. Still using stress as an example, it may warn the system that the operator identified something threatening for the activity or itself. At the same time, if the system is aware of the threat, it can be one indicator that the operator is responding to this threat. On a more general scale, stress may impact the decision making of the operator, leading to the deployment of different strategies, or may cause errors through unnecessary quick actions. While interesting, our knowledge on the impact of those different states on the train driving activity remain limited. Until further knowledge is produced in this regards, our focus shall be oriented on factors known to be the main issues in railway operation: fatigue and vigilance.

Cardiac activity analysis is among the majors biosignals considered in this domain. This can be explained from both the critical role of the heart in human activity, it very tight relationship with the autonomic nervous system, as well as the ease of measurement. Using cardiac activity, one can analyse both psychological and physiological state [6]. Two characteristic are especially interesting for fatigue and vigilance detection: heart rate and its variability. Hearth rate variability is particularly interesting in the fact it is linked to the respiratory rhythm (respiratory sinus arrhythmia), which permit the complementary probing of respiratory rhythm.

Cerebral activity analysis is a more straightforward way of probing for operators' state. This method is however limited by the acquisition and processing requirement. Indeed, whenever electroencephalogram (EEG) or near infrared spectrography (fNIRS) is chosen, the operator is required to wear a usually cumbersome headset. This fact tend however to change slowly, with more lightweight and wireless headset penetrating the market while demonstrating exploitable results. In addition to usual state and activity analysis, some works point to the possible study of cognitive fatigue thanks to fNIRS [7].

Occulography can be used for both activity analysis and nervous systems activation analysis. Indeed, analysing the visual scanning activity and gaze entropy can be interesting means to estimate operators' activity. On the other side, parameters linked to unconscious blinks such as blink rate are dependent on the autonomic nervous system, and as such can be good indicators of physiological state. Occulography have the benefit to exist both in wearable format and in integrated format within the workspace.

The analysis of muscle tonus is also a good indicator of an operators' physiological state. By monitoring muscle response to stimuli or more simply the change of posture (ex. a more relaxed posture on a chair) or facial features, one can monitor high an low nervous activation states. Facial feature prove to be especially rich in information, providing approximate of emotional states as well. While muscle response may be difficult to monitor in real situations, posture and facial features are easier to monitor thanks to seat-mounted sensors and/or cameras.

Finally, a lesser used signal is electrodermal activity. Nervous activation impact multiple features of the skin, such as conductivity thanks to the activation of sweat glands, or even skin temperature. Those measures are however difficult in real condition, from both the mean of recording and the strong susceptibility to noise.

From this collection of signals, one shall be able to have a good understanding of an operators' current state, both physiological and psychological. Those information may however not be enough to reliably follows an operator vigilance state, as human state and its link to the activity may not be as straightforward.

2.2 Perception & evaluation of human activities

Being able to estimate an operators' state is important for the safety of the system, but also have limitations. While, for example, stress can easily be monitored though cardiac and skin parameters, differentiating between situational stress and stress originating from personal life is quite difficult ; that is, if we consider stress-related signals only. Through the analysis of activity, it should be possible to identify known action patterns related to the situation and abnormal or misfitted patterns. Correlating identified states and ongoing activities may benefits both analysis, leading to more robust situation identification and a better fitted readiness estimation. This would however require a thorough analysis of the activity, accounting for the high variability of situations and behaviors.

Probing for operators' action on the system is a first step to both identify patterns of actions and to monitor the activity during exploitation. A similar approach was undertaken by Alstom [8] on tramways, with the objective to complement the usual vigilance monitoring system. The proposed system monitor the activation of multiple standard commands within the train cab to activate the vigilance monitoring system. This system is however limited to monitoring the activity on the tramway, without true pattern recognition apart from command repetition filtering to prevent unconscious validation.

This situation present two main issues to the implementation of a reliable substitute for the usual vigilance monitoring system. First, as acknowledged by the authors, this system does not account for phases of the activity where no commands are pressed. It's common practice in order to save energy to accelerate up to the desired speed and release the throttle to benefits from the vehicle inertia. During those normal phases, the system is unable to perform its monitoring task and rely back on the standard vigilance monitoring system. Second, this system still rely on the hypothesis that activity is equal to vigilance. This hypothesis was rejected during the studies of vigilance monitoring systems [2, 3], where drivers were found able to perform basic activities in very low vigilance situations. As such, this system act mostly as a relief from the traditional system, which used to cause musculo-skeletal issues.

This offer a valuable experience for the design of a vigilance monitoring system. Human activities on the commands can be part of the system to relieve the operator, but shall not be the main component in it current state. One shall consider the whole activities and means to perceive it, including for example oculometry regarding the operator information gathering activity. One shall as well consider the activity in its entirety and not the most common subsets. A normative or descriptive approach of the activity may miss the edge cases, were human intervention is especially meaningful. A formative analysis, such as the one introduced by Rasmussen [9, 10], may benefits the vigilance monitoring system through the understanding of deploy-able strategies and global objectives pursued by operators, even in unknown scenario. Using such activity analysis, in conjunction with a more comprehensive activity monitoring and bio-signals analysis may enable more efficient and reliable vigilance monitoring systems.

3 Bio-signals monitoring & cooperation

On the basis of a reliable state estimation, actions have to be taken to strive towards safer operation. Currently deployed vigilance monitoring systems are very simple in this matter: they prompt the operator for an immediate input and trigger an emergency brake if the operator fails to answer immediately. This curative and highly conservative approach, while understandable regarding the stake at risk, is quite inefficient. One should encourage, providing the system is highly reliable, a preemptive action to maintain or restore vigilance before its level sinks to reach critical thresholds. At the same time, one shall take in consideration the impact of preventing reaching said thresholds in the global activity, especially regarding fatigue accumulation.

3.1 Applications of a bio-signal feedback loop

While it appears to be lesser-known in engineering, using "bio-feedback" has shown potentially interesting results in the medical field. The principle is not very different from the notion of feedback loop in a technical system, where connecting the system's output to the inputs enables automatic adaptation and regulation. In this case, however, the feedback is from physiological measurements [11]. In the medical field, bio-feedback use this principle in an attempt to train patients to recognize and adapt their behavior, when facing simple situations such as stress or more complex and durable situations such as cancer therapy. While there may not be sufficient information to support the basis of the method and its efficiency in the medical field, a systematic review suggest potentially positive results [12].

Although lesser-known in engineering fields, applications of bio-feedback are not entirely absent from litterature. In the work of Aidman et al. [13], the equivalent of a bio-feedback is provided (although in a very simplified way) and hints of behavior adaptation can be observed. Systems which process physiological or behavioral data in order to alert an operator, e.g. driver monitoring systems, could be associated to an extend to bio-feedback. It is to note that some variations in results are observed, depending on used bio-signals and targeted objective, leading to cautions from some medical practitioners [14]. When investigating which bio-signal is best indicated for a target state, it is important to consider that not all conditions can be addressed using bio-signals.

Following the work of Aidman et al. [13], as well as the increasing literature on driver monitoring and alert systems, one may expect vigilance monitoring and assistance systems based on a similar bio-signal feedback loop principle to have an impact on drowsiness and fatigue management. We thus postulate that, with a system capable of identifying with confidence the driver state and an appropriate feedback for the identified state, we may encourage a behavioral adaptation to face the decrease of vigilance and rise in fatigue. It is important to emphasize that such system would not clear the issue of fatigue itself, arising naturally during activities ; a behavioral adaptation would only temporarily lower the associated risks, until proper resting becomes necessary.

As much as using bio-signals appears as an interesting approach to the issue of waning vigilance, it is in no way a solution to the global problem of fatigue. On the contrary, we may expect an additional feedback loop to worsen drivers' fatigue. Following Phillips review of fatigue definition [15], the root cause of fatigue seems to be exertion, whether mental, attentional, or other. Keeping the driver involved in the vigilance task is a form of attentional exertion, preventing cycles of regeneration, i.e. rest. For a practical aspect, the continuous solicitation of the driver may improve performance on a short term, but will likely worsen it on the long term.

As such, one shall considerate the addition of bio-signals feedback to a higher level, i.e from an activity organisation point of view, as to not degrade the operators' work condition nor the safety of the system.

3.2 Cooperation & levels of automation

Monitoring the state of fatigue and vigilance of the operator can provide continuous support during the activity and contributes to the global objective of Human-Machine Cooperation (HMC). Indeed, a role of HMC is to study how the operator and technical systems work together and assist them in adopting a cooperative approach to the activity. Following the principles of HMC, the capabilites of each agent, in this case the train driver and assistance systems such as a feedback based vigilance monitoring system, can be determined and respectively assigned to their Know-How (KH) or their Know-How-to-Cooperate (KHC) [16, 17]. Notably, the KHC of each agent determines their ability to interact and cooperate with others and can be divided in specific sub-functions, among which are Interference Detection (ID) and Interference Management (IM) with other agents (cf. Figure 1). The notion of interferences, either positive or negative, is thus central in a cooperative process [18], as their detection drives interactions, such as through the monitoring of an agent's attentional state.

According to the definition of HMC principles, we consider that "two agents are cooperating if i) each one strives towards goals and can interfere with the other, ii) each agent tries to detect and process such interference to make the other's activities easier" [19]. As presented in [20], this cooperation may happen on a shared task, such as managing a vehicles' speed, but also between different abstraction levels such as guiding a vehicle though unforeseen events (tactical level) while reconsidering the global strategy to account for the disturbance (strategic level). In the context of this study, in managing the driver's vigilance and fatigue, the role of cooperation would be focused on the operational level (cf. Figure 1) when trying to induce a change of behavior from an agent. A tactical level approach could also be imagined. Indeed, if a great part of the driving activity is ensuring safety at all times, then surely one may choose to adapt the activity to ensure vigilance is always to the most fitted level. Using a feedback loop from bio-signals, we could encourage high vigilance when most needed, and resting periods could be encouraged when the operator's vigilance is not necessary. This hypothetical application is explored in the following part.

4 The future cooperative activity

4.1 Towards increasing cooperation in railway transportation and teleoperation

The railway driving activity, in which the human operator interacts and shares tasks with various technical systems, is not unfamiliar with cooperation. Indeed, the train driving activity is categorized into several Grades of Automation (GoA), ranging from purely manual driving (GoA0) to fully autonomous operation (GoA4) [21]. Notably, in GoA1 applications, the activity performed manually by the driver who is assisted by Automatic Protection Systems (ATP) which can intervene in the activity in case of emergency or when specific errors are made by the driver, such as ignoring signalling. In GoA2, the driver may even be assisted by Automatic Train Operation (ATO) to automate some of the driving tasks, but the driver must still monitor the driving activity at all times.

While GoA3 and GoA4 trains have already been implemented in nearly closed environments such as subways, current technology does not allow for completely autonomous and safe operation in most open-world environments, and human expertise remains required [22]. Although most of the driving tasks can usually be performed by an autonomous system, limitations are due to certain events that are still difficult or yet impossible to manage without onboard personnel, such as the evacuation of passengers in case of an emergency [22]. Unlike subways or other closed environments, the potential for unexpected events is also much higher, particularly when there are interactions with inhabited areas or roads. Being guided by the track, the train has fewer degrees of freedom to handle these unplanned events when compared to other domains [23]. These limitations affect the operability and acceptability of GoA4 operations until certain barriers, especially those related to safety [24, 25], are resolved.

In this context, the immediate future of railway activities seems to lie within GoA2 applications, where cooperation with increasingly advanced technical systems and the driver is maximal. Additionally, in [26], train teleoperation, where the driver pilots the train from a distant site, is proposed as a potential extension to GoA2 activity. In teleoperation, however, the driver is affected by important information loss and must rely on what can be sent by the train to the distant driving platform [17]. Because of this, the driver, who can usually perceive part of the activity through auditory information and kinaesthesia, is now limited to mostly visual information, increasing visual cognitive workload and fatigue.

As the authors of [27] and [28] suggest, the driver's Situation Awareness (SA) is generally negatively affected by the automation of some tasks. In a situation of teleoperation, SA is even more affected as it is more difficult to project into the activity, notable due to the aforementioned reduced quality of information from a distance [29]. According to [30], there is a clear correlation between task management, SA and mental workload. A remote driver interacting with a highly automated system, able to share some of the driving tasks, could thus prone to both hypovigilance as they must monitor the activity while having reduced authority, and prone to fatigue because of an overload of the visual channel.

4.2 The role of future assistance systems in the management of driver fatigue and vigilance

As the systems become increasingly advanced and automated, and more tasks of the driver, or remote driver in teleoperation, are shifted towards technical systems, cooperation with both agents is not only expected, it is also necessary. Future technical and assistance systems and drivers must thus have an appropriate KHC to work together and manage potential conflicts. In this context, what role could

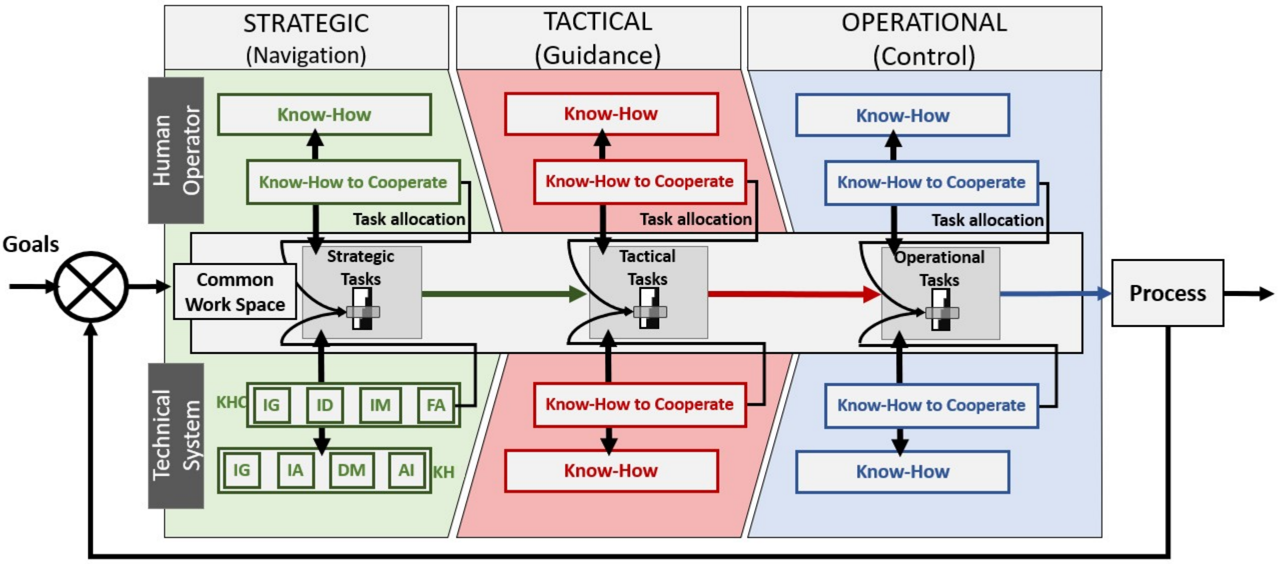

Figure 1. Human-machine cooperation (HMC) model including levels of automation

be expected from these assistance systems in managing conflicts linked to the driver's fatigue and vigilance?

As previously mentioned, being able to monitor more precisely the driver's fatigue during the activity, and their respective level of vigilance is crucial and could be increased through the use of a bio-signal feedback loop. Currently, most trains are equipped with some form of "dead man's switch" that is supposed to constantly monitor whether the driver is incapacitated and conscious. Trains from the French railway company SNCF are equipped with VACMA (which could translate to "*automatic vigilance with maintained pressure control*"). Although efficient to some extent in determining whether the driver becomes unconscious, this device is not able to detect hypovigilance and is often prone to automatisms [3], sometimes persisting even while drowsing. Being able to detect hypovigilance and fatigue could be a highly beneficial way to upgrade these systems and ensure that the driver is actually actively focused in the activity.

While the previous part mentioned a potential risk of increasing fatigue through providing additional information to the driver, in the form of bio-signals, it suggests a potential application in adaptatively managing vigilance. In a more hypothetical outlook on future railway applications, to reduce the effects of monotony and preserve the driver's fatigue throughout the activity, assistance systems could perhaps be given a much higher authority during some parts of the activity. By temporarily reducing the driver's authority, this could allow some time to potentially rest in anticipation of more intensive tasks. A similar strategy to adapt the level of interaction with the system, to balance the driver's workload and effort during the activity, is proposed in [31]. Naturally, this would require technical systems to work under higher automation levels, perhaps considering parts of the activity as within a semi-closed environment, which is still hypothetical for current safety standards. Similarly, as mentioned previously, in low effort portions of the operator's activity, the SA would also decrease, making the "onboarding step", when the driver is pushed back in the activity, more challenging. Nonetheless, this adapatative stategy could prove beneficial if the driver can be more vigilant and efficient during more effortful tasks.

4.3 Presenting vigilance and fatigue feedback to the driver

Having presented some hypothetical roles of future driver assistance systems, as well as the potential of integrating a bio-signal feedback loop to alleviate the risks of fatigue and hypo-vigilance, a next step is to investigate how they can be presented to the driver. The objective is to provide train drivers, or remote drivers, a feedback of their current level of fatigue or vigilance, from measured bio-signals mentioned previously. To that end, it is important to determine what solution of interface could be used to provide this information. While still hypothetical and not exhaustive, this part will attempt to offer some insight on potential solutions before they can be experimented in upcoming experimental campaigns.

Perhaps the simplest and most obvious solution is to display, at all times and within the visual user interface of the driving platform, an indicator on the driver's current state of fatigue or vigilance. This indicator could be displayed as a numerical value, assuming value could be explicit and usable for the operator. Otherwise, it could be displayed in a way that illustrates the different states, such as a gauge that changes along with the corresponding signal, or through a specific set of pictograms. However, while such solution can provide continuous information to the driver, it may not be always beneficial. Indeed, as mentioned previously, as another source of visual information to get from the driving interfaces, these indicators could contribute to an increasing cognitive overload and an increase in fatigue. Additionally, while a change of behavior is expected from the feedback, one must ensure that it is not a source of stress or frustration to the driver, especially if the driver does not recognize the change as an accurate reflection of their vigilance state. A potential alternative could be to reduce the potential information cluttering by hiding the current fatigue or vigilance state, and its evolution, from the driver, and only alert when the measured signals approach defined critical thresholds. Ultimately, different solutions must be implemented and evaluated before we can confidently state their advantages and disadvantages the train driving activity.

5 Conclusion

The flaws of currently deployed vigilance monitoring systems have been acknowledged for some time, and the recent advances in the field of human state monitoring encourage the redefinition of such systems. Notably, they fail to properly assess the driver's attention and fatigue state, a crucial issue to the train driving activity, which could be emphasized even more in remote driving situations. Multiple signals are interesting to monitor for such objectives, but designers of future assistance and attention monitoring systems must be careful not to deploy a system which does not properly consider the human activity. Monitoring the activity is key to contextualize the operators' state and reliably analyze the current situation. With the help of the study of human factors and human-machine cooperation, we suggest potential solutions on how future vigilance monitoring systems could integrate the monitoring of physiological bio-signal and present them in a feedback loop to the human operator. While they seem to present beneficial properties to the driver's activity, further investigation is necessary to design proper interface and assess their efficiency and applicability.

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