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TECHNICAL REPORT

D3.2: Report on solutions to mitigate heat stress for workers of the transportation sector

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1. EXECUTIVE SUMMARY

The transportation sector employs 11 million people accounting for ~5.1% of total employment in EU and ~4.6% of total GDP. The sector is central to Europe's economic growth, but also of importance for everyday mobility and safe transportation of citizens. Occupational tasks and main heat issues may be divided into two main areas:

1) **Driving/steering/navigation of vehicles with safety as the primary factor of importance**. During these tasks the workers metabolic rate and internal heat production is usually low, but heat stress may threaten attention, performance in combined cognitive and fine motor tasks, therefore, influence driving skills and safety. 2) **All associated services and logistic** (i.e. more manual tasks such as loading/unloading the vehicle or manual handling of goods in warehouses etc. including work in both conditioned/unconditioned spaces) or office work. The present work primarily focuses on 1) and challenges related to occupations in vehicle cabins, while tasks outside vehicles resemble other industrial work. We refer to parallel Heat-Shield reports on solutions to mitigate heat stress for workers in the construction and manufacturing industries for detailed advice).

The major issues contributing to discomfort and heat stress in vehicle cabins is excessive external heating of the cabin air and cockpit surfaces (i.e. greenhouse effect), and the heterogeneity of exposure related to solar radiation, shading elements and conditioning systems. This is especially burdensome since there is no or limited possibility to seek shadow, change body orientation or lower the work pace during driving. In addition, a high vigilance level is required during work despite the monotonous work periods. On the other hand, dehydration (due to irregular eating times, avoidance of physiological breaks, drinking as distraction during work) may be aggravated by heat stress and strongly interfere with driving skills and safety. Heat-Shield studies have also identified that heat stress (without dehydration) may impair complex motor performance and especially so if tasks are alternating (i.e. multitasking activities are more affected than "stand-alone" tasks). However, even mild dehydration (~2% equal to levels prevalent for 70% of all workers across Europe) will aggravate the negative influence from heat stress and tasks performance relying on combined cognitive and motor function become markedly impaired. The loss of productivity in this case may relate to increased number of transportation accidents, decreased road safety and elongated breaks between shifts. Furthermore, sleep deprivation and fatigue (due to unsocial working hours, sleeping with lack of comfort and hygiene in the cabin, sleeping in the heat) can further contribute to decline of cognitive performance.

In the long term, irregular eating times and bad nutrition at inappropriate times, and long hours of sitting and the irregular rhythm of the life of employees in the sector may impair the workers' health condition (i.e. overweight and obesity, high blood pressure and metabolic disorders such as diabetes and hyperlipidemia) promoting cardiovascular diseases and sleep related disorders. Deteriorated health conditions make drivers even more sensitive to exposure to hot environmental conditions especially when higher physical activity is periodically demanded.

To avoid excessive heating of the cabin/vehicle and prevent negative effects on cognitive performance and productivity, the **following mitigation measures have been identified as highly relevant:**

- **Prevent/minimize the risk of sleep deprivation** – secure the ability to get enough sleep before and between work-shifts, i.e. provide possibility for recovery/sleeping in cool environment, following circadian rhythm with working times whenever possible
- **Prevent dehydration** – even mild hypohydration influence visuo-motor performance. Supply with cold drinks and remind workers to rehydrate between work-shifts
- **Reduce solar radiation effect on the cabin and the driver** – e.g. via conscious use of AC, use of low-transmissivity/high-reflectivity glazing elements, solar shading solutions (sunshades), and high-reflectivity paints
- **Reduce heat load on the driver by increasing the air flow in case AC is not available** to facilitate evaporation of sweat and prevent excessive increase in core body temperature
- **Consider using clothing with good moisture management properties** (work/sport clothing with low resistance to evaporation) to increase evaporative heat loss particularly in very hot cabin conditions. Consider seat ventilation in this case.

- If **re-scheduling of work or changed timing** of certain tasks is possible prefer cooler times of the day for performing the most demanding manual tasks and use peak heat periods for activities with low metabolic heat production

In addition to the above listed solutions and strategies focussed on lowering heat load on the driver/worker, the transport sector should also aim at reducing AC-requirement and develop more energy efficient methods for prevention of high temperatures inside vehicles. Our **advanced modelling analyses** indicate that combined use of low-transmissivity/high-reflectivity glazing elements and high-reflectivity paints can reduce heat/radiative load on cabin substantially and **lower peak AC loads/requirements by almost 40%**.

This can provide a **substantial improvement in vehicle fuel efficiency and tailpipe emissions**, and both vehicle producers and consumers should consider this as attractive; both from an economic point of view and in relation to the environmental footprint perspective.

2. Introduction

It is quite clear that occupational heat stress can negatively affect workers health and their performance capacity, which subsequently may lower productivity and income for the individual and/or company costs directly related to a loss in working efficiency or indirectly via illness/sickness. The present report is part of a series of five papers (industry specific reports on each of the key EU sectors [manufacturing, construction, transportation, tourism and agriculture]). Overall the papers focused on defining, screening and optimizing appropriate technical and biophysical solutions to counter the negative impact of high thermal stress imposed by the combination of adverse environmental conditions, industrial heat production, the workers own/internal metabolic heat production, conditions and confounding factors such as protective clothing or other work related factors that may conflict with heat dissipation.

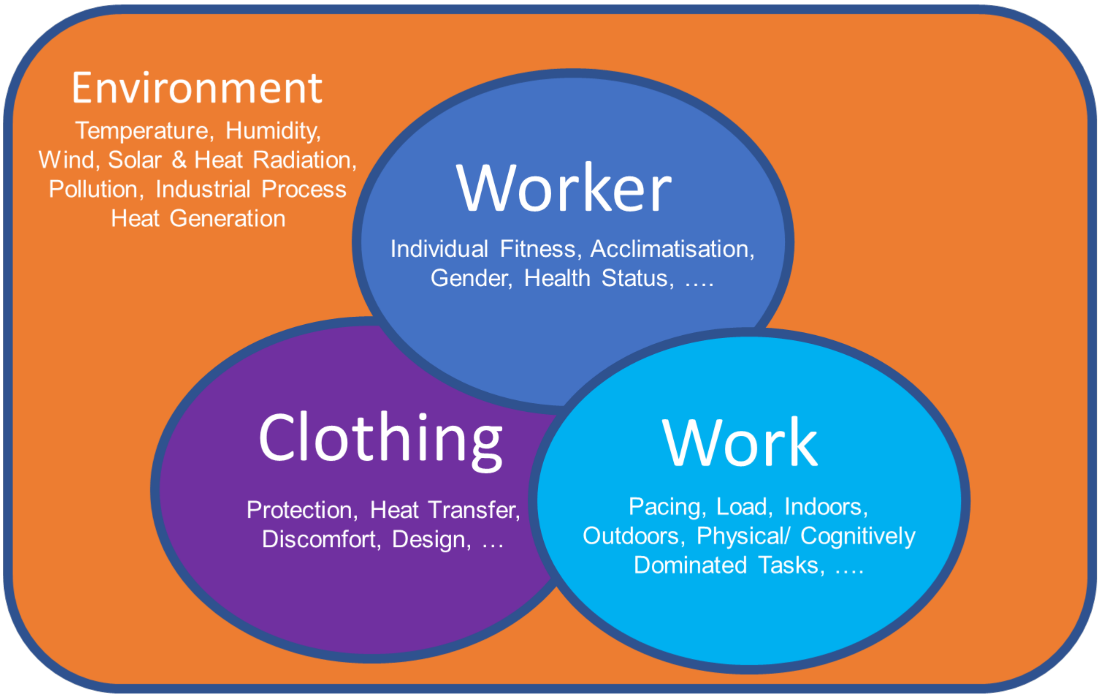

Figure 1 Overview on occupational aspect of human heat balance

Human function depends on a balance between internal (metabolic) heat production and heat-exchange with the environment. When a worker is physically active, the metabolic energy release will increase in proportion to the work intensity and, hence, increase heat production in the body. If not released to the environment, this heat will warm up the worker, increase heat strain, impair both physical and cognitive function and potentially provoke fatal overheating. Therefore, to keep workers safe and avoid decrements in functionality, the produced heat shall be balanced by heat lost from the body (skin) to the environment, which can be by dry heat loss (primarily air convection and radiation) and/or by sweat evaporation. For occupational settings, it is characteristic that in addition to climatic conditions (with air temperature, solar radiation, humidity and wind speed as the factors of importance) the local environment may also be highly influenced by the industrial settings (see figure 1). The warmer and more humid the environment (micro-climate around the worker), the more difficult it is to lose heat. In addition solar radiation or radiation from industrial processes, will further add to the heat load while wind/ventilation can benefit dry heat loss as long as the air temperature is below 35 degrees. In addition, wind can facilitate evaporation and hence benefit the overall heat balance even at higher environmental temperatures.

When considering solutions to lower heat stress, any practice that may either lower workers internal heat production (e.g. optimizing the work procedures) or facilitate heat dissipation (including lessening of the constraining effects that e.g. clothing may impose) or directly cool the body (e.g. ingestion of cold drinks or ice) can be beneficial. This can range from behavioural and biological interventions/adaptations to technical solutions that may assist heat dissipation (e.g. increasing air flow, cooling vests or air conditioning) or lower the environmental heat load (e.g. reducing solar radiation). In accordance with this overall context, the present report will consider the specific solutions screened and identified as both effective and feasible to implement for workers in the transportation sector.

This report on solutions for the transportation sector focuses on the industry specific issues, needs and exposure characteristics of workers from the transportation sector in order to identify ways to mitigate the corresponding heat stress. The focus is in proposing adaptation measures including minimizing sleep deprivation, hydration, advanced glazing and paint solutions, shading alternatives, work time planning and smart clothing solutions, given the particular exposure of transportation workers. While assessing the capacity and potential of these adaptation measures to mitigate workers' heat stress, the report will also put special attention on determining the specific requirements of the different solutions, and their compatibility with the intended application environment.

3. Industry specific issues

3.1 Distribution of work scenarios across the transportation industry

In 2014, the transportation sector and storage services sector employed 11 million persons accounting for 5.1% of its total employment in the EU, and representing 4.6% of GDP [1, 2]. Around 53% of them worked in land transport (freight and passenger road transport, railways including train drivers, rolling stock and track maintenance workers, control officers, cleaners, caterers, customer service professionals, and pipelines), 3% in water transport (sea and inland waterways including fisheries), 4% in air transport (civil aviation and ground staff) and 25% in warehousing and supporting and transport activities (such as cargo handling, storage and warehousing) and the remaining 16% in postal and courier activities. The sector has an important role to play in Europe's economic growth and job opportunities. 18% of the working population in this sector is women. Table 1 shows typical work types in various modes of transport and related issues to consider, such as air-conditioning, glazing, work outdoors and indoors, physical activity, and harmful emissions.

Common exposure scenarios were defined for the different modes of transport (types A to H) in Table 1. The most relevant scenarios potentially affecting the well-being of the employees were identified. The number of potentially affected workers spending most of their working time in either closed or open cabins with or without air-conditioning (scenarios A and C, respectively) is estimated to reach 7 million employees, which is the largest population in this sector. The second largest group of occupations is related to work outdoors in shielded or unshielded setting that is also found in other sectors such as agriculture and manufacturing.

Table 1. Scenarios of typical work types in various modes of transport and related issues [1].

Mode of Transport	Employment 2013 (in 1000, [2])	Duty	Environment	Issues	Scenario type
Road transport (freight)	2938 (28%)	Driving	Cabin (closed)	Air-conditioning, glazing	A
		Load / unload	Outdoor / hall	Physical activity, temperature fluctuation, acclimatization	B
Road transport (passenger)	1991.4 (19%)	Driving	Cabin (open)	Temperature fluctuations, draught	C
Warehousing / support	2635.8 (25%)	Load / unload	Outdoor / hall	Physical activity, temperature fluctuation, acclimatization	B
		Warehouse clerk	Hall	(non-air-conditioned) hall	D
Railway	559.6 (5.3%)	Drivers	Cabin (closed)	Air-conditioning, glazing	A
		Control officers	coach	Temperature fluctuations, draught	C
Pipelines	28.5 (0.3%)	Maintenance	outdoor	Extreme climates (temperature fluctuations, intense sunlight), physical activity	E
		Fire fighter	Fire incidents	Extreme temperatures, radiation, physical activity	F
Inland water transport	40.3 (0.4%)	Load / unload	Outdoor	Physical activity, temperature fluctuation, acclimatization	B
		Seafarer	Outdoor	Extreme climates -> temperature fluctuations, intense sunlight	G
Sea transport	164.8 (1.6%)	Seafarer	Outdoor	Long periods being at sea (hot environments, intense sunlight)	G
Air transport	350.2 (3.3%)	Pilot	Cabin	solar / UV ray /radiation exposure	H
		Ground staff	outdoor	Physical activity (refueling aircrafts, ground engineers), high temperature	B
Postal / courier activities	1812.6 (17%)	Driver	Cabin (closed)	Air-conditioning, glazing; temperature fluctuations	A

3.2 Working conditions in transportation sector

Both organisation of work and working conditions are recognised as risk factors for psychological strain, health problems and even mortality due to cardiovascular disease [3]. Figure 1 presents the aspects of the working conditions in transportation sector in the year 2000. The profile is unfavourable in almost all potential risk dimensions identified, compared with the average of all other sectors (Z-transformed figures; EU average is 0). The sector is at risk in terms of ambient conditions (noise, vapours, danger, vibrations, high/low temperatures, radiation), ergonomic conditions, working non-standard hours and long working hours, as well as organizational risks such as heavy job demands, lack of control and inability to develop one’s skills at work.

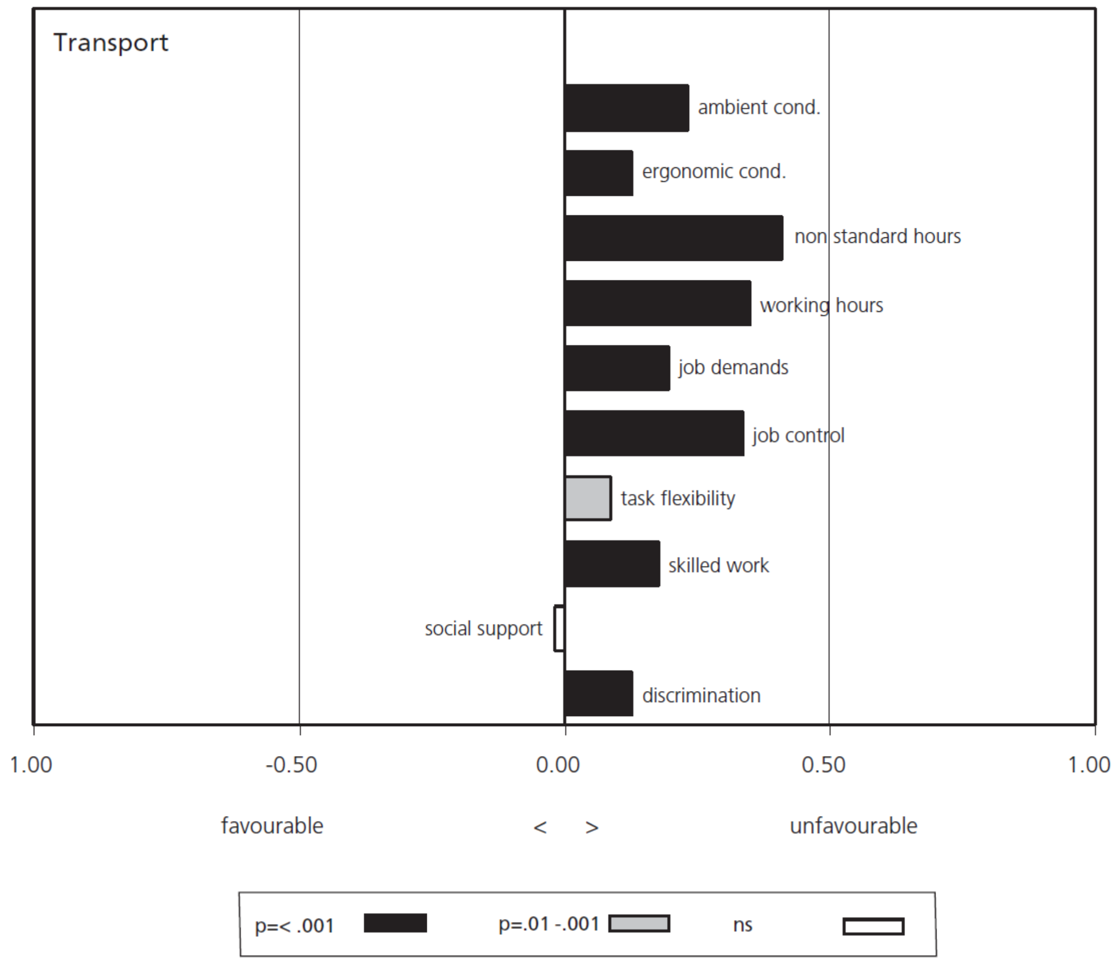

Figure 1. General profile of working conditions in the transportation sector[3].

In this project the special interest is focused on ambient environmental conditions, especially the experience of thermal environment. The European Foundation for Improvement of Living and Working Conditions in its report on ‘EU road freight transport sector: Work and employment conditions’ states that extreme temperatures and temperature fluctuations are regarded as a specific negative aspect of the physical work environment of drivers working in road transport of goods. In the Nordic countries, working in extreme cold temperatures or exposure to variations in temperature is perceived as particularly problematic. Musculoskeletal injuries are more likely to occur, especially when performing heavy physical loading and unloading activities in a cold environment, after a long period of sitting in a warm cabin. Several countries mention specific risks related to climate for drivers in public transport. In Greece, for example, exposure to excessive heat and variable workplace temperatures contribute to poor ambient conditions for urban transport drivers. In Denmark and Finland, exposure to draught is mentioned as a specific risk for public transport drivers.

Another important source of work stress is the increasingly competitive environment in which European road transport companies have to operate, which widens the nature of the tasks required from truck drivers. Tasks traditionally performed by warehouse or stock managers are now taken over by the drivers themselves, such as loading and unloading.

3.3 Working time in transportation sector

The percentage of employees working more than 40 hours a week is high in the sector compared with national levels for all sectors [3]. Similar trend is seen with regards to working overtime. For example, in Denmark, 67% of employees in freight transport by road work more than 45 hours a week, in Belgium, 21% of drivers work more than the maximum number of hours one or three days a week, in Austria the working weeks of between 70 and 80 hours are fairly common in international transport, in United

Kingdom 60% of employees in the sector work more than 48 hours a week. Working time in road transport of persons tend to be shorter than in freight transport by road. The long working hours are connected to earning possibilities even against regulations that limit driving and working hours. External factors responsible for long working hours are congestion and traffic jams resulting often in earlier start to the working day.

The EU working time regulation No 561/2006 [4] on the harmonisation of certain social legislation relating to road transport imposed restrictions on the amount of hours worked per day and forced regular resting periods (Table 2).

Table 2. Restrictions on the amount of hours worked per day imposed by EU working time regulation No 561/2006 [4].

driving periods	9 hours daily driving limit (can be increased to 10 hours twice a week); maximum 56 hours weekly and 90 hours fortnightly driving limit;
breaking periods	45 minutes break after 4.5 hours driving (can be split into two periods of 15 and 30 minutes);
resting periods	11 hours regular daily rest (can be reduced to 9 hours up to three times a week, or can be split into two periods of 3 and 9 hours); 45 hours weekly rest (can be reduced to 24 hours when full rest is taken in any fortnight, no more than six consecutive 24 hours periods between weekly rests).

Despite the above regulations aim at protecting the drivers' health and safety, implementation/compliance is often threatened by difficulties in finding enough drivers and employee's dissatisfaction with limited possibilities to earn money. Furthermore, part-time work is not very common in the transport sector in all European countries (average employment rate well exceeding 90%) due to reluctance of sharing the vehicle with other drivers and difficulty with scheduling and logistics [3]. Employees in the transport sector have also more non-standard working patterns, compared with the national average by increased rate of unsocial hours, e.g. during the evening, night and morning and working during weekends and holidays. Working at weekend and night is extensively used to make use of the road network when it is relatively empty.

3.4 Negative health effects of the work situation in transportation industry

An important element of quality of work and employment is the degree of safety of the physical environment reflected in occurrence of occupational accidents, occupational diseases and absenteeism. Both the passenger and freight transport sectors are characterised by a higher number of accidents compared to the total economy with possibly small accidents being underreported. In addition, working accidents in the transport sector generally result in more severe consequences than those in other sectors. Overall, the frequency and percentage of fatal accidents within land transport and especially within freight transport by road is two to five times greater than the average for all sectors [3]. Fatigue is an important risk factor of the long working hours and driving at night (monotony and drowsiness) that may lead to road accidents. Furthermore, sleeping in the cabins while away from home has negative consequences on the quality of sleep and rest because of the lack of comfort and hygiene in the cabin and often the fear of the load being stolen. Just-in-time delivery schedule in freight sector as well as bus and tram driving in passenger transportation were reported to be associated with health problems caused by mental stress.

Longer working hours are related to the greater chances of suffering from sleeping and digestive disorders, irritability and swollen lower limbs. Most EU countries indicate that the sector experiences a relatively high number of mobility problems (diseases of the musculoskeletal system, particularly back, neck and shoulder problems) in comparison with the national average. These problems are related not only to the lifting heavy weights but also to exposure to extreme temperature changes and droughts in both cold and hot environments (long sitting in warm cabins followed by outdoor work in cold, droughty and overcooled cabins in summer to compensate for solar load). Hearing problems are also often reported. Irregular eating times and bad nutrition at inappropriate times, and long hours of sitting and the irregular rhythm of the life of employees in the sector may impair the workers' health condition (i.e. overweight and obesity, high blood pressure and metabolic disorders such as diabetes and hyperlipidemia) promoting cardiovascular diseases and sleep related disorders in the long term. Deteriorated health conditions make the drivers even more sensitive to exposure to hot environmental conditions especially when higher physical activity is periodically demanded [5]. It may be presumed that only a few truck and bus drivers continue to work until the normal retirement age of 65 years due to health reasons.

3.5 Summary of problems that can be aggravated during heat waves or in hot environment

- Environmental heat exposure (no possibility of self-pacing, body orientation change, or seeking greater shadow, limited work avoidance during worst time of the day, droughts, large temperature gradients)
- Frequent dehydration (irregular eating times, avoidance of physiological breaks, drinking as perceived distraction during work)
- Sleep deprivation and fatigue (unsocial working hours, sleeping with lack of comfort and hygiene in the cabin, sleeping in the heat)
- Keeping alertness and high cognitive performance despite the monotonous work periods.
- Already small mistakes may have fatal consequences for the worker and road safety.

4. Identified/screened solutions

4.1 Secure sleep quality and quantity

The thermal environment is a key determinant of sleep quality because thermoregulation is strongly linked to the mechanism regulating sleep. An increased wakefulness as well as decreased time in slow-wave sleep phase (SWS) and rapid eye-movement sleep phase (REM) are typical effects observed in heat exposure. REM is thought to play a role in learning, memory, and mood and SWS is crucial for memory consolidation. Heat-related sleep disruptions occur both in young as well as in the elderly and one does not adapt even after 5 days of continuous daytime and nocturnal heat exposure. Furthermore, the same negative effects of heat exposure on SWS were even found for partial sleep deprivation where sleep pressure is increased. These results suggest a strong effect of heat load on sleep stages, which is related to thermoregulation during sleep.

In a study conducted within this Heat Shield project, a significant drop in productivity upon termination of the heatwaves was observed [6]. This indicates a potential cumulative effect of heat exposure due to the inability of the worker to recover from thermal strain at work during heat waves amongst others due to reduced sleep quality. In a follow up study, an attenuation of sleep maintenance during heat waves was found [7]. This can be one reason for increased sleep deprivation, impaired recovery and reduced productivity. For this reason, a cool environment (by air conditioning and other mitigation measures as presented below) to maintain sleep is highly recommended.

4.2 Hydration and heat stress

It is quite clear that both occupational health (safety, minimizing risks for accidents etc.) and productivity (workers performance capacity) is highly dependent on the ability to maintain both cognitive and motor functions. The combination of tasks (physiological functions) related to safe driving, relies on the ability to register an input (visual, sensory or auditory), cognitive processing of the combination of input (conscious and unconscious decision-making) before providing an appropriate output (motor response or reaction).

Previous studies on the effects of heat and hydration have mainly focused on strenuous physical exercise performance (where high heat stress both with and without dehydration have clear detrimental effects), but many occupations involve less intense activities and tasks depend on attention or executive functions rather than maximal exercise capacity. For such tasks there is a discrepancy between the marked reductions in occupational productivity, reported safety incidents and loss of working capacity in ecological settings and results from RCT lab studies (where performance in choice reaction type of tasks e.g. is unaffected and hydration have minor and very variable effects on cognitively dominated tasks). In completed Heat-Shield studies [8, 9] we have investigated this issue/discrepancy by systematic investigation of effects of low-moderate-high heat stress on simple, complex, combined and cognitively dominated tasks [9] and subsequently looking at the effects from moderate (2%) hypohydration. In addition, it has previously been shown that both driving [10] and flight simulations [11] are affected (i.e. increase in number of driving/flight errors) when moderate dehydration is present.

We refer to Appendix 1 for detailed discussion, but for brevity in this report conclude:

High heat stress (when dehydration is prevented) has limited effect on simple motor function and simple choice reaction type of tests, but marked effect on complex motor performance and especially so if tasks are alternating (i.e. multitasking activities are more affected than “stand-alone” tasks).

If subjects/drivers become dehydrated (even low levels of hypohydration – observed for ~ 70% of all workers across Europe [8]) the effect from high-heat stress becomes highly aggravated and both simple and complex motor function as well as combined and cognitively dominated functions are negatively affected. Complex motor tasks are in this context highly vulnerable, but we also observe a doubling of errors in cognitively dominated tasks (math solving) signifying the importance of preventing hypohydration for maintained occupational safety for workers exposed to high heat stress.

These observations translate into the following guidelines/suggested strategies:

- If possible minimize “multitasking” – reduce tasks complexity for heat stressed workers – i.e. simplify the occupational tasks during high-heat periods as those tasks are more vulnerable to heat stress compared to “uni-tasking” and simple assignments, however, this may not always be feasible.
- Prevent any dehydration as even small deficits (2% reduction in bodyweight ~ urine specific gravity > 1.020) have marked effects when combined with heat stress. While the effect of dehydration without or with low heat stress is small and variable, the combined effect is marked – exacerbating effects of hyperthermia/heat-stress on all type of tasks.

Others factors/solutions to be considered (of importance for hydration aspects or “direct” impact on central nervous system (CNS) functioning):

- Prevent solar radiation directly on the head – One study [12] show effect on physical performance – but none has evaluated effects of direct exposure on the head – i.e. if radiation directly influence the cerebral cortex). However, data from our ongoing pilot study, indicate that solar radiation direct to the head impair cognitive performance especially in regards to the complex motor task. The mechanism behind this is not clear, but we are investigating if it separately increases CNS temperature or relates to whole body hyperthermia (from the elevated heat load).
- Caffeine consumption – should also be considered when working in HOT environments. It is well established that caffeine consumption benefit exercise performance in cool to temperate conditions [13, 14] and may benefit pre-motor planning and execution of motor response, as it may act on the network controlling motor function [15]. However, there may be an upper limit for caffeine ingestion when working and exercising in the heat. It has been shown that caffeine ingested as coffee has marginally lower hydration profile compared to still water [16], but the literature does not support that caffeine increase diuresis [17]. However, workers should consider staying within “safe” limits of caffeine ingestion (<5mg/kg bodyweight).

4.3 Properties of the cabin and interaction of the driver and the cabin

The properties of the cabin elements affect the heat transport between the environment and the cabin occupants. This is particularly evident during summer and especially for activities implying long exposures to solar radiation (e.g. long-distance transportation), because of the resulting high thermal loads on the cabin. To counter these thermal loads, drivers often rely on air conditioning (AC) to maintain the cabin temperature within comfortable ranges, which has important detrimental effects on fuel efficiency and tailpipe emissions. This highlights the importance of efforts to find ways to minimize the AC loads associated with the transportation sector.

For this purpose, we have analysed the thermal loads on a typical European long-distance truck, during an entire work day, considering the environmental conditions found in summer in the southern regions of Europe (known to have very hot summers). Furthermore, we have investigated the effect of changing the optical properties of the windshield, side windows and external paint used to protect the vehicle metal surfaces, over the thermal loads affecting the cabin, and thus the overall AC loads required to cool it. For greater representativeness, we have considered ranges of optical properties for the mentioned cabin elements, based on currently-available products or technologies. We considered warm and cool versions for each cabin element, depending on the amount of solar radiation they reflect / transmit.

We concluded that preferring windshields / side windows with a transmissivity of 0.33 instead of 0.79 / 0.84, can reduce the peak AC loads by 9-16% and 3-7%, for south and west vehicle directions, respectively. Furthermore, the use of external paints with reflectivity of 0.70 instead of 0.04 can reduce the peak AC loads by 23-25%. If the above changes are considered for all of the mentioned cabin elements at the same time, then reductions in peak AC loads of up to 38% can be obtained.

These results obtained highlight the importance of carefully choosing the optical properties of cabin surfaces, because of the potential impacts on the load AC loads, and therefore, the vehicle fuel efficiency and tailpipe emissions, all of which affect the environmental footprint of the transportation sector as a whole.

From the above results, the following guidelines/strategies can be suggested:

- When choosing a vehicle, carefully choose the optical properties of the cabin elements
  - Prefer “cool” windshields & windows (i.e. low-transmissivity / high-reflectivity glazing)
  - Prefer “cool” paints (i.e. high-reflectivity paints)
- Use sunshades in all glazing elements (to reduce direct/diffuse thermal loads)
- Keep windows fully closed when AC is ON (if the ambient is warmer than the cabin)
- Avoid setting the AC temperature too low compared to the ambient temperature (to minimize fuel consumption and tailpipe emissions)
- Keep windows slightly open when parked under the sun (to minimize soak temperature)
- Choose covered parking places (to decrease soak temperature / AC loads).

4.4 Clothing

Since the majority of the drivers’ surface area (skin) is covered by clothing, it is highly relevant to consider the effect of clothing on body heat dissipation and how it is associated with thermal burden on the worker. Depending on the type of work, casual clothing made of lighter fabrics or a uniform may be required, which offer different degree of freedom to regulate the clothing thermal and evaporative resistance at workplace. Beside the properties of fabric used in garments, the air gap underneath the clothing constitutes the bulk of the thermal insulation and the magnitude of contact area between the skin and clothing greatly influence the moisture transport from the skin surface to the garment. In real life conditions, the trapped air between the human body and the garment has uneven shape and vary over the body parts as a consequence of the complex geometry of human body, garment design and limpness of the fabric. This also implies that the air gap and contact area distribution will greatly change with a substantial change of body posture.

Recent research in this area showed that the thermal and evaporative resistance of clothing ensemble will substantially decrease in seated (driving) posture due to collapse of the air gaps and increase of the contact area between fabric and skin [18] (Figure 4). However, in this case, the additional insulation provided by the seat in the back, buttocks and the thigh region needs to be considered (see section 4.5). Since the majority of data on garment and ensemble parameters relates to the standing posture measured using a thermal manikin [19, 20], some further investigation have been done to translate these data to parameters adequate for sitting posture (Appendix 2). Based on data for air gap thickness and contact area available in Mert et al. [18] and clothing model developed at Empa (Appendix 3) we have attempted the calculation of the ratio between average air gap thickness between driving and standing position and possible consequent change of thermal and evaporative resistances for some exemplary light clothing sets in regular and loose fit. The results showed the decrease of thermal resistance by up to 30% and of evaporative resistance by up to 60% for sitting posture due to collapse of the air layers under the casual garments. This fact demonstrates the advantage of the seated posture in dissipating heat to the environment more efficiently than when standing.

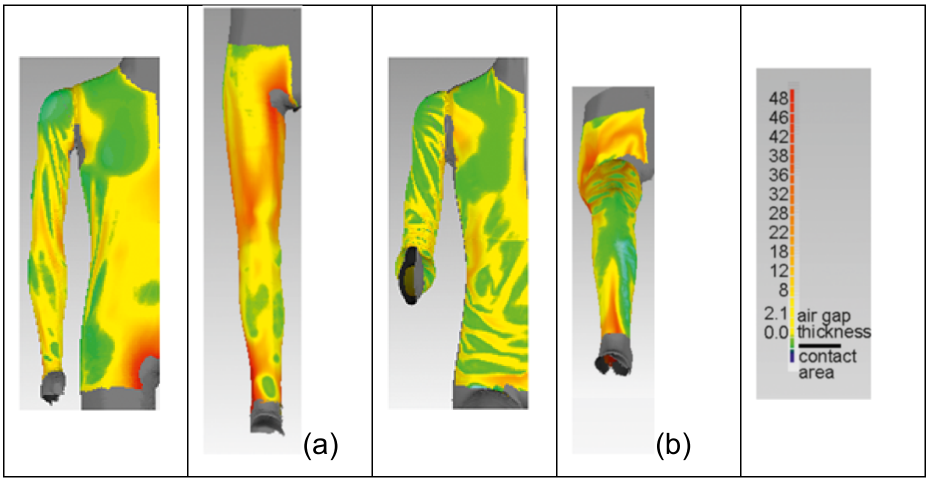

Figure 4. Comparison of air gap distribution and contact area between standing (a) and driving (b) positions [18] where contact area is depicted in green and air gap thickness in yellow to red colours.

The study by Mert at al. [18] showed that in many cases the contact area between the garment and the skin doubled when seated. This fact gives the opportunity of optimizing evaporative heat dissipation from the body by using fabrics with good evaporative cooling performance. This includes moisture management properties supporting optimal sweat wicking on the fabric surface to enable sweat evaporation close to the skin and enhance evaporative cooling efficiency. To avoid any reductions in evaporative cooling efficiency, transversal wicking within the fabric and moisture absorption of the fabrics should be avoided. For this purpose, thin fabric layers and manmade fibres like polyester or polyamide are recommended for hot days in the driver cabin.

4.5 Interaction with the seat

Since the driver is in direct contact with the seat for a gross of the working time, (surface) material properties and structures of seats should be considered. In addition, any integrated ventilation or cooling systems may have an additional effect on the thermal condition of human body inside a cabin, in particular in hot conditions. The seat thermal and evaporative resistance, its thermal inertia and the magnitude of the contact area of the body to the seat play major role for the heat transfer between the human body and seats.

Automotive seats consist of seat covers and seat cushions beside the inner construction elements with the first two having the greatest effect on heat and moisture transfer. Seat covers are usually made of fabrics or leathers and provide the minor part of the overall thermal resistance of the seat (0.012-0.093 m^2K/W) but may significantly contribute to evaporative resistance of the seat (4.1-102.1 m^2Pa/W).

The seat cushions constitute the thicker part of seats, and hence the bulk of the thermal resistance. Depending on the type of the cushion material the total thermal resistance of seat may range 0.40 -0.55 m^2K/W for exemplary airplane seats [21] with increasing trend for vehicle seats which have the cushions typically thicker than 4 cm. The evaporative resistance of cushions out of molded foam and spacer knits was reported to be 147 and 81 m^2Pa/W, respectively [21]. In extreme environmental conditions (heat and cold) the thermal capacity of the seat might need to be considered for the estimation of the transient contact cooling or heating of the driver after entering the heated up or cooled cabin. The thermal capacity of molded foams used for seats is dependent on the temperature and cushion construction and approximates 955-1500 J/kgK [22]. Assuming that an average seat includes ca. 3 kg of foam, the energy reaching the human body when touching the seat heated up to 45°C and at skin temperature of 35°C would lead to short-term (ca. 5 min) heat load of 45 kJ.

The contact area with the seat is correlated with body weight and height and approximates 15-20% of the total body area for subjects with body mass index range of 18.4-29.4 (weight range of 52-99 kg), respectively [23]. Roughly, this contact area is divided equally between the back and buttocks. In case of actively ventilated or cooled seats, beside the contact area between the seat and the body the heat sink magnitude is of major importance to address adequately the heat extracted from the body. Based on literature survey and internal studies the most frequently quoted number regarding the heat flux extracted by the ventilated/cooled seats is between 20-40 W/m^2 [24]. The lower values apply more to the back and the larger values to the buttocks. Even if larger heat sink would be technically achievable the local cooling and heterogeneity of exposure makes the cooling effect unpleasant for the user. Study by Zhang et al. [24] shows that there is a sweet spot where the largest acceptability of cooling by the seat occurs as shown in Figure 4. This fact makes this solution as a heat mitigation measure as rather ineffective and costly.

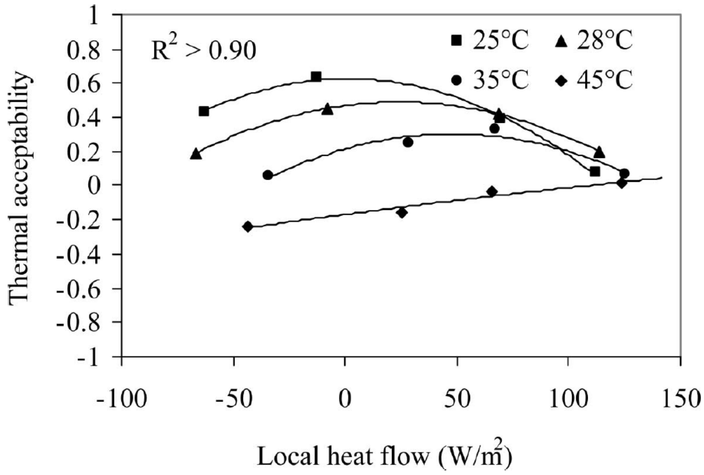

Figure 4. Effect of local heat flow (positive when towards seat) on thermal acceptability in summer conditions (the temperatures are ambient room temperatures and each point on the figure represents the mean of 24 votes in each condition) taken from Zhang et al. [24].

4.6 Comparison of mitigation strategies

In order to quantify the effect of various heat exposure mitigation strategies in transportation sector, the simulation approach was used where the thermo-physiological and thermal comfort aspects, such as body core temperature, water loss, thermal sensation and skin wetness related to thermal and wet comfort were compared. For this purpose the human thermoregulation model (FPCm - Fiala Physiological and Comfort model, Ergonsim, Germany) was used [25, 26], which has been extensively validated in previous studies (general accuracy of 0.30 for core and 1.08 °C for skin temperature with 50% of validation exposures being conducted in heat) [27-29]. The input parameters were derived from literature for vehicle exposed to solar radiation during summer day (Appendix 3) and the model represented an average person (35 year old, weight of 71.4 kg and height of 169.7 cm).

The compared heat strain mitigation strategies possibly available in transportation industry are related to the use and setting of air-conditioning, shading, seat ventilation, reduction of clothing and work scheduling. The baseline exposure included 9h working day (8:00-17:00 with 1h lunch break at cooler shaded environment) including AC set to 25°C, solar radiation (direct and diffused) changing during summer sunny day, relative humidity of 30%, heterogeneous air speed in the cabin (0.05-0.6 m/s), clothing with short sleeves and long pants adjusted for seated posture and seat, mean radiant temperature of 41°C [30] and typical activity level of the driver (1.5 MET). The strategies applicable to vehicle environment were as follows:

(a) Air conditioning usage. Three cases of air temperature of 35, 30 and 25°C represent different levels of AC usage that would correspond to different energy consumption in the vehicle. The air temperature has great effect on decreasing the body core temperature to the save limit of 38°C as well as on the water loss through sweating. Both thermal comfort parameters, however, remained in the uncomfortable range (Figure 5a).

(b) Using additional vehicle settings. To simulate shading the direct solar radiation was excluded from the simulation. Shading might be the most powerful method of heat strain mitigation reducing both body core temperature and water loss significantly, as well as keeping the comfort parameters closer to the comfortable range. A possibility of effective body cooling at the contact with the seat can be offered by a ventilated seat that increases evaporation of sweat. As described in section 4.5 only certain maximal cooling load can be used in such case without causing local discomfort (20W/m^2 at the back and 40W/m^2 at buttocks and thighs), however. This strategy improved only wet comfort by keeping skin wetness close to comfortable range (Figure 5b).

(c) Reducing clothing. When clothing was reduced by assuming shorts instead of trousers and no socks the overall physiological and comfort response of the body was only minimal (Figure 5c).

(d) Incorporating breaks. Additional breaks in cool and shaded environment helped increasing comfort and reducing the body core temperature periodically, which also contributed to lower water loss (Figure 5d).

In overall, usage of AC seems to be unavoidable to keep the core temperature in a save range below 38°C threshold. Combining it with possibly maximal shading of the driver will improve the physiological and comfort status of the body and may lead to decreased demand of AC. The indicated water loss needs to be replaced by drinking to not lead to dehydration and associated loss of cognitive performance and health. In addition, reducing clothing and incorporating breaks in cool shaded environment whenever possible may additionally support heat strain mitigation.

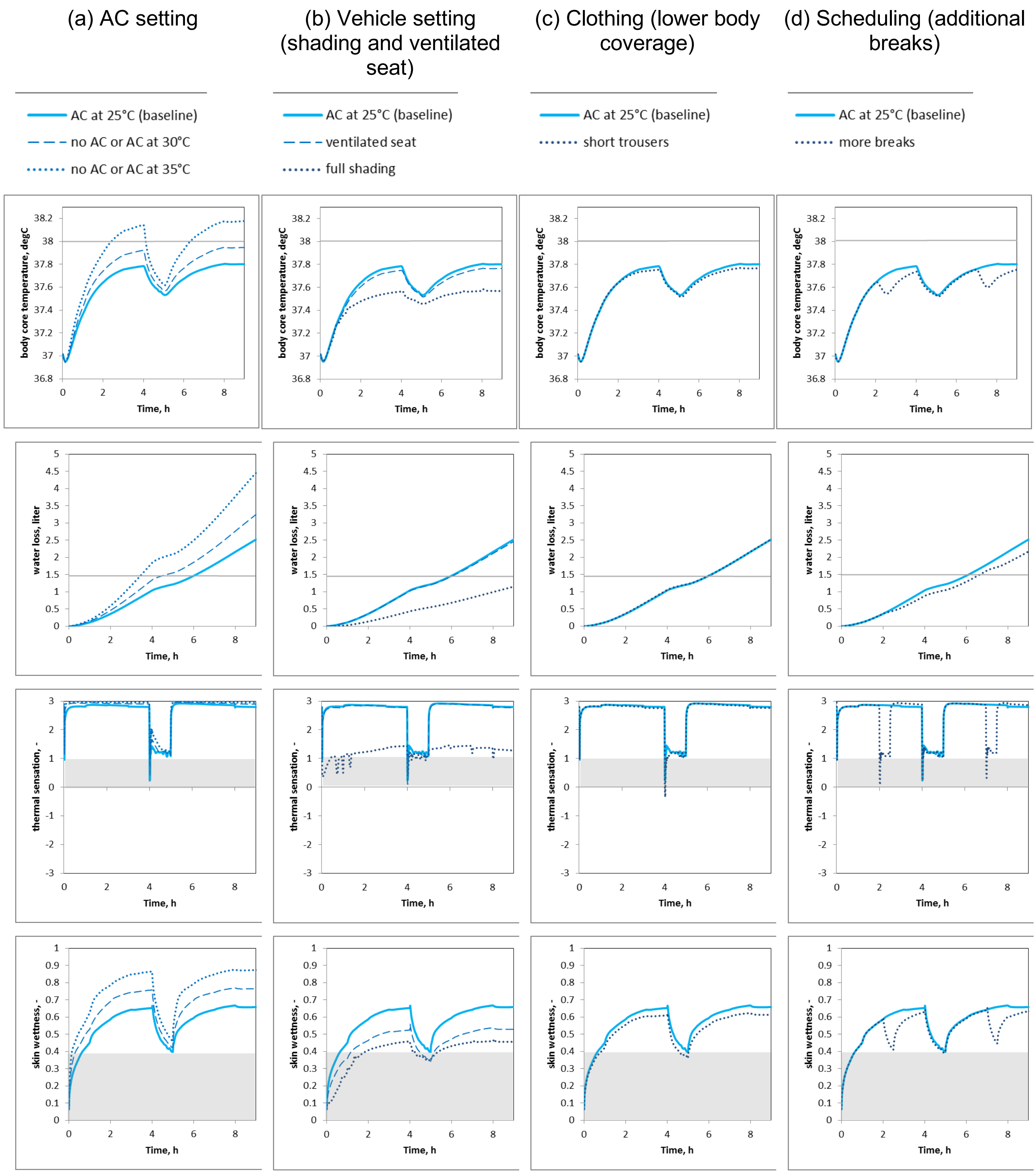

Figure 5. Body core temperature, water loss through sweating, thermal sensation and skin wetness predicted for various heat strain mitigation strategies during 9h working period. Grey lines indicate 38°C safety threshold for body core temperature and 2% dehydration level for water loss if not re-hydrating. Grey zones in thermal sensation and skin wetness diagrams indicate regions associated with thermal and wet comfort, respectively.

4.7 Conclusions

To avoid excessive heating of vehicle and prevent negative effects on cognitive performance and productivity, the **following mitigation measures have been identified as highly relevant:**

- **Prevent/minimize the risk of sleep deprivation** – secure the ability to get enough sleep before and between work-shifts, i.e. provide possibility for recovery/sleeping in cool environment, following circadian rhythm with working times whenever possible.
- **Prevent dehydration** – even mild hypohydration influence visuo-motor performance. Supply with cold drinks and remind workers to rehydrate between work-shifts.
- **Reduce solar radiation effect on the cabin and the driver** – e.g. via conscious use of AC, use of low-transmissivity/high-reflectivity glazing elements, solar shading solutions (sunshades), and high-reflectivity paints.
- **Reduce heat load on the driver by increasing the air flow in case AC is not available** to facilitate evaporation of sweat and prevent excessive increase in core body temperature.
- **Consider using clothing with good moisture management properties** (work/sport clothing with low resistance to evaporation) to increase evaporative heat loss particularly in very hot cabin conditions. Consider seat ventilation in this case.
- If **re-scheduling of work or changed timing** of certain tasks are possible prefer cooler times of the day for performing the most demanding manual tasks and use peak heat periods for activities with low metabolic heat production.

In addition to the above listed solutions and strategies focussed on lowering heat load on the driver/worker, the transport sector should also aim at reducing AC-requirement and develop more energy efficient methods for prevention of high temperatures inside vehicles. Our **advanced modelling analyses** indicate that combined use of low-transmissivity/high-reflectivity glazing elements and high-reflectivity paints can reduce heat/radiative load on cabin substantially and **lower peak AC loads/requirements by almost 40%**.

This can provide a **substantial improvement in vehicle fuel efficiency and tailpipe emissions**, and both vehicle producers and consumers should consider this as attractive; both from an economic point of view and in relation to the environmental footprint perspective.

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