# $CO_2$ Project

## *$CO_2$ effects on drivers' state and performance*

**Publik rapport**


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# 1 Sammanfattning

Koldioxid ($CO_2$) är en lukt- och färglös gas som finns i atmosfären i en koncentration av cirka 400 ppm (delar per miljon). Även om koldioxid inte är giftigt i sig kan exponering för mycket höga koncentrationer (> 10 000 ppm) ha måttliga till allvarliga konsekvenser för människors hälsa, t.ex. högt blodtryck, yrsel, illamående eller till och med livshotande tillstånd som hyperkapni eller medvetslöshet. Kortvarig exponering för måttligt höga nivåer (1000-5000 ppm) är också känt för att ge milda symtom som trötthet, obehagskänsla eller huvudvärk. På senare tid har studier visat att såndana halter även kan påverka människans fysiologiska och kognitiva tillstånd. Några av dessa effekter är ökad hjärnaktivitet i samband med sömnighet, lägre hjärtfrekvens och sämre kognitiv förmåga i tester som kräver koncentration och beslutsförmåga. Dessa effekter har kopplats till prestationsproblem i miljöer med förhöjd koldioxid, t.ex. skolor, kontor och flygplan.

Dessutom har måttligt höga $CO_2$-nivåer också upptäckts i fordon som körs med HVAC-enheten (uppvärmning, ventilation och luftkonditionering) i recirkulationsläge (RC). Detta system används ofta för att minska inflödet av föroreningar utifrån (t.ex. vid trafikstockningar) och/eller för att maximera luftkonditioneringseffekterna, särskilt under sommaren. I elbilar där det krävs batterikraf även för uppvärmning, används återcirkulationsläget även vintertid för att förlänga körsträckan. En konsekvens av att RC läget aktiveras är dock att koldioxidhalten snabbt ökar i kupén.. I olika studier har man noterat $CO_2$-nivåer på 1 000-5 000 ppm efter bara 5-10 minuters körning. Detta visar att ett stort antal förare dagligen kan utsättas för koldioxidkoncentrationer som kan påverka deras välmående och, ännu viktigare, deras förmåga att köra säkert. Denna potentiella effekt finns det, så vitt vi vet, inte särskilt mycket forskning på.

För att åtgärda denna kunskapslucka syftade detta projekt till att belysa de möjliga effekterna av måttligt höga $CO_2$-nivåer, som ofta förekommer i fordon, på förarens mående och prestation. Dessutom analyserades i detta projekt hur andra faktorer, såsom förarens mentala arbetsbelastning och körtid, påverkar effekterna av koldioxid. Detta andra mål bygger på den idé som lyfts fram i två nyligen genomförda granskningar om att $CO_2$-effekter kan vara lättare att upptäcka när kraven på arbetsuppgifterna är tillräckligt höga. Förutom att lära sig mer om koldioxidens betydelse för körsäkerheten syftade projektet också till att ge rekommendationer till Senseair (partner i projektet) om styr- och larmgränser hos framtida koldioxidsensorer i fordon.

För att uppnå dessa mål utformades en studie på VTI:s simulator i Linköping (Sverige). Simulatorn placerades i ett 24 $m^3$ stort tält, inuti vilket koldioxidhalten kunde styras och kontrolleras. Detta gjordes med hjälp av ett system som gjorde det möjligt att injicera ren $CO_2$ blandad med frisk luft i lämpliga koncentrationer. $CO_2$-nivån i tältet reglerades automatiskt med hjälp av sensorer och ett slutet kontrollsystem. Trettiotvå friska vuxna deltagare (i genomsnitt 41 år gamla) utförde två kognitiva testuppgifter (vid dator) samt körde simulatorn vid koldioxidhalter på 700 ( normal nivå inomhus), 1 500 och 3 000 ppm. Körscenariot bestod av en landsväg med milda kurvor och lätt trafik, vilket simulerar monoton körning. Varje körning varade i 40 minuter. Var femte minut fick förarna muntligt rapportera sin sömnighet med hjälp av Karolinkas sömnighetsskala (1 mycket alert - 9 mycket sömnig). I början eller i mitten av varje körning inleddes en 20 minuter lång auditiv uppgift som utfördes samtidigt med körningen. Syftet med denna uppgift var att öka deltagarnas kognitiva belastning för att se hur den påverkar koldioxidens effekter. Dessutom övervakades deras hjärt- och ögonaktivitet med elektroder för att analysera deras vakenhetsnivå under körningen.

I korthet visade våra resultat att exponeringen vid 1500 ppm ledde till de starkaste effekterna på deltagarnas subjektiva och fysiologiska tillstånd samt på deras prestation. Specifikt var den objektiva och subjektiva sömnigheten högre, och den laterala fordonskontrollen var sämre (dvs. större lateral variation och fler linjeöverskridanden). Hastighetsvariationen var också större i detta tillstånd, dock endast när den auditiva uppgiften ingick. Vid 3000 ppm var den enda effekt som observerades större objektiv sömnighet (dvs. längre blinkningar) jämfört med grundtillståndet. Körprestationen var dock likartad och i vissa fall något bättre än i grundtillståndet. Även om betydande effekter av körtiden på de flesta subjektiva, fysiologiska och prestationsmässiga mått upptäcktes, förvärrades dessa inte av exponering för förhöjda CO2-nivåer, vilket vi hade trott.

Detta är den första studien hittills i sitt slag som undersöker koldioxidens effekter på förarens mående och prestation under monotona förhållanden. Även om resultaten inte är entydiga och måste replikeras, fann vi att måttligt förhöjda CO2-halter påverkade förarförmågan.. Å ena sidan är storleken på de observerade effekterna ganska liten, så man förväntar sig inte att CO2, i de koncentrationer som analyserats, skulle orsaka allvarliga problem i trafikförhållanden med låg komplexitet. Trots detta har nyligen gjorda undersökningar visat att koldioxidens effekter på prestation kan vara större vid mer krävande uppgifter. Därför kan koldioxidens inverkan på förarförmågan vara större i mer krävande trafikmiljöer (t.ex. vid stadskörning med många olika trafikanter). Å andra sidan följer koldioxidens effekter på körförmågan enligt våra observationer kanske inte ett linjärt dos-responsmönster. Det vill säga, högre CO2-nivåer är inte nödvändigtvis skadligare än lägre nivåer. Även om det inte finns någon uppenbar förklaring till detta fenomen har andra studier rapporterat liknande effekter. Aktiveringen av odefinierade kompensationsmekanismer som svar på förhöjda CO2-nivåer (i vårt fall 3000 ppm) skulle kunna förklara detta icke-linjära mönster. Investering av ökad mental ansträngning, hyperventilation eller aktivering av metaboliska processer på cellulär nivå som svar på förhöjda CO2-nivåer är några hypoteser som föreslagits i litteraturen och som bör beaktas i framtida studier.
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# 2 Executive summary in English

Carbon dioxide ($CO_2$) is an odourless and colourless compound present in the atmosphere at a concentration of approximately 400 parts per million (or ppm). While $CO_2$ is not toxic per se, exposures to very high concentrations (> 10000 ppm) may have moderate to severe implications for human health, e.g., high blood pressure, dizziness, nausea or even life-threatening conditions such as hypercapnia or loss of consciousness. Short-term exposures to moderate-high levels (1000-5000 ppm) are also known to produce mild symptoms such as fatigue, discomfort or headache. More recently, studies have shown they could also affect the human physiological and cognitive state. Some of these effects include increases in brain activity related to sleepiness, lower heart rate and worse cognitive performance in tests assessing concentration or decision-making capacity, among others. These effects have been linked to performance problems in ecological environments with elevated $CO_2$, including schools, offices and airplanes.

Moderate-high $CO_2$ levels have also been detected inside vehicles driving with the HVAC unit (heating, ventilation and air conditioning) in recirculating mode (RC). This system is often used to reduce the inflow of pollutants from outside (e.g., when traffic is congested) and/or maximize the air conditioning effects, especially during the summer. In e-cars, drivers also activate the RC to reduce energy consumption when cooling down the warm air from outside. A consequence of enabling the RC system, however, is a rapid build-up of respiration-derived $CO_2$ due to a lower air exchange rate. In fact, different studies have detected moderate-high $CO_2$ levels (1000 – 5000 ppm) after just a few 5-10 minutes of driving. This evidence suggests that a large number of drivers may frequently expose themselves to $CO_2$ concentrations that could affect their state and, more importantly, their ability to drive safely. This potential effect, however, has received no attention in the literature.

To address this knowledge gap, the present project aimed to elucidate the possible effects of moderate-high $CO_2$ levels on driver fitness and performance. In addition, this project analyzed the influence of other factors, such as driver mental workload and driving time, on the effects of $CO_2$. This second objective builds on the idea highlighted by two recent reviews that $CO_2$ effects may be more easily detectable when task demands are sufficiently high. Besides learning about the role of $CO_2$ on driving safety, this project also aimed to provide recommendations to Senseair (partner in the project) on the calibration of future in-vehicle $CO_2$ sensors.

To address these objectives, a study was designed to be conducted on the VTI simulator in Linköping (Sweden). The simulator was placed inside a 24$m^3$ tent specially built for this project in order to manipulate and regulate the indoor $CO_2$ levels. This was done by means of a system that allowed pure $CO_2$ mixed with fresh air to be injected into the appropriate concentrations. The indoor $CO_2$ level was automatically regulated through sensors and a closed-control system. Specifically, thirty-two healthy adult participants (41 years old on average) performed two computerized cognitive tasks and drove the simulator under levels of 700 (normal indoor), 1500 and 3000 ppm in counterbalanced order. The driving scenario consisted of a rural road with mild curves and light traffic, thus simulating monotonous driving. Each drive lasted 40 minutes. Every 5 minutes, the drivers were asked to verbally report /her level of sleepiness using the Karolinka Sleepiness Scale (1 very alert - 9 very sleepy). At the beginning or in the middle of each drive, a 20-minute auditory task started and performed simultaneously to the drive. The aim of this task was to increase the cognitive load of the participants in order to see its influence on the effects of $CO_2$. In addition, their heart and eye activity were monitored by electrodes to analyze their level of alertness during driving.

Briefly, our results indicated that the exposures at 1500 ppm led to the strongest effects on our participants' subjective and physiological state, as well as on their performance. Specifically, objective and subjective sleepiness was higher, and lateral vehicle control was worse (i.e., greater latera variability and more line crossings), compared to the other conditions. Speed variability was also greater in this condition, although only when the auditory task was included. Under 3000 ppm, the only effect observed was greater objective sleepiness (i.e., longer duration of blinks) compared to the baseline condition. Driving performance, however, was similar and, in some cases, slightly better than the baseline condition. Finally, although significant effects of driving time on most subjective, physiological and performance measures were detected, these were not exacerbated by exposure to elevated levels of $CO_2$, against our prediction.

This is the first study of its kind to investigate the effects of $CO_2$ on driver fitness and performance during monotonous conditions. Although the results are inconclusive and need to be replicated, we found evidence that moderate-high concentrations of $CO_2$ could affect the state and performance of drivers. However, these effects need to be qualified. On the one hand, the size of the observed effects is quite small, so we might expect that $CO_2$, at the concentrations analyzed, would cause serious performance problems in low complexity traffic conditions. Despite this, recent reviews suggested that the effects of $CO_2$ on performance can be larger under more demanding tasks. Therefore, the impact of $CO_2$ on driving performance could be greater in more demanding traffic environments (e.g. in urban driving with a variety of road users around). On the other hand, according to our observations, the effects of $CO_2$ on performance may not follow a linear dose-response pattern. That is, higher levels of $CO_2$ may not necessarily be more harmful than lower levels. Although there is no obvious explanation for this phenomenon, other studies have reported similar effects. The activation of ill-defined compensatory mechanisms in response to elevated $CO_2$ levels (in our case, 3000 ppm) could explain this non-linear pattern. The investment of more mental effort, increments in respiration breath and depth, or the activation of metabolic processes at the cellular level in response to elevated $CO_2$ levels are some hypotheses proposed in the literature that should be considered in future studies.

# 3 Background

Carbon dioxide ($CO_2$) is an natural compound which is present in the atmosphere at approximately 400 parts per million (or ppm). Such concentrations, however, concentrations tend to be higher in indoor spaces, mostly  due to the build-up of of $CO_2$ released during occupants' respiration. Normally, indoor levels fall between 600 and 800 ppm but may reach 5000 ppm in poorly ventilated areas. This is why indoor $CO_2$ concentrations have long been used to proxy indoor air quality(Hung-F, 1989). Examples of daily indoor environments where elevated concentrations have been found include office buildings(Allen et al., 2016; Reardon & Shaw, 1993), schools (Fisk, 2017; Krawczyk & Wadolowska, 2018; Ruggieri et al., 2019) or residential buildings (Mainka & Zajusz-Zubek, 2019; Wang et al., 2014).

## 3.1 $CO_2$ effects on human health

*Severe health effects*

$CO_2$ is not toxic *per se*; however, exposure to high concentrations may have moderate to severe implications for human health. The type and severity of such effects mostly depend on the exposure levels and the frequency and duration of the exposures. Acute exposures to extremely high levels between 50000 to 100000 ppm may increase blood pressure and produce dizziness, nausea or even life-threatening conditions such as hypercapnia or loss of consciousness(Jacobson et al., 2019). By contrast, short-term exposures to moderate-high levels (1000-5000 ppm) generally produce mild symptoms affecting occupants' well-being, such as subjective feelings of fatigue and discomfort or headache (Lu et al., 2015; Muscatiello et al., 2015). To prevent these health and comfort issues in occupational environments, different agencies have recommended $CO_2$ limits that should not be exceeded. Such thresholds range from 700 ppm above outdoor concentrations, as is the case for the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), to 5000 ppm, established by the Occupational Safety and Health Administration (OSHA).

*Temporal effects of $CO_2$ on the human psychophysiological state.*

Recently, a growing number of studies have reported effects of moderate-high $CO_2$ levels on the psychophysiological state of humans as well as on their performance. Some effects include increased sleep-related brain activity (Bloch-Salisbury et al., 2000; Snow et al., 2019), lower heart activity (Chen et al., 2020; Snow et al., 2019; Vehviläinen et al., 2016) and detriments in the performance of cognitive tests assessing addition and subtraction (Liu et al., 2017; Zhang et al., 2015), concentration and proofreading (Kajtár & Herczeg, 2012; Lowe et al., 2018), inhibitory control (Coley et al., 2007) and, especially, decision-making (Allen et al., 2016; Scully et al., 2019). Decrements in the performance of more ecological tasks have also been reported. For example, a review by Fisk et al. (2017) found several studies reporting lower performance of students completing academic tasks under poorly ventilated conditions, i.e. the $CO_2$ level was higher. In office environments, decrements in the performance of workers have also been linked to elevated $CO_2$ concentrations (Federspiel et al., 2002; Wargocki et al., 2004). In a more safety-critical example, Allen et al. (2016) reported that pilots' performance in a simulated flight task decreased when exposed to levels of 2500 ppm compared to lower levels (1500 and 700 ppm).

Despite these results, it should be noted that no clear consensus exists in the literature on the actual effects of moderate $CO_2$ concentrations. As suggested by Du et al. (2020) and Jacobson et al. (2019), the lack of consistency across studies may be explained by methodological differences across studies (e.g., different $CO_2$ levels, exposure times, experimental designs, type and difficulty of the tasks or interindividual differences between participant), but other mechanisms such as extra mental effort investment could also play a role.

**$CO_2$ build-up inside vehicles**

Moderate high $CO_2$ levels have been often detected inside vehicles driving with the HVAC unit (heating, ventilation and air conditioning) in recirculating mode (RC). This system is often used to reduce the inflow of pollutants from outside (e.g., when traffic is congested) and/or maximize the air conditioning effects, especially during the summer. In e-cars, drivers also activate the RC to reduce the energy consumption when cooling down the warm air from outside (Li et al., 2018). It is unclear how often drivers use the RC mode. However, Barnes et al. (2018) reported that 72.5% of the drivers activated it all year-round. A consequence of enabling the RC system, however, is a rapid build-up of respiration-derived $CO_2$ due to a lower air exchange rate. Different studies have detected moderate $CO_2$ levels after just a few minutes of driving. For example, after only 5 minutes, Mathur (2008) detected 1200, 2000, 3150 and 4025 ppm for one, two, three and four occupants, respectively. Also, Luangprasert et al.(2017) detected levels of 10000 ppm after 30 minutes of driving with four occupants. Similar results have been replicated in more recent work(Angelova et al., 2019; Hudda & Fruin, 2018; Luangprasert et al., 2017). In addition to the number of occupants and driving duration, other factors that facilitate the accumulation of $CO_2$ are the car size and age and driving speed (Mathur, 2008, 2011).

Based on this evidence and the potential effects of $CO_2$ on human psychophysiological state, it is possible that many drivers frequently expose themselves to $CO_2$ levels that could impair their capacity to drive safely. In special cases, such exposures may occur for prolonged periods, as is the case for some commuters or professional drivers (e.g., truck drivers) and with many occupants inside (e.g., bus drivers). Provided that sleepiness and fatigue, typical symptoms induced by $CO_2$, are behind 20% of all traffic accidents(Dawson et al., 2018), it becomes necessary to shed light on its role in driving performance and traffic safety. To date, this remains largely understudied and was therefore investigated in this project.

# 4 Purpose, research questions and methodology

The aim of this project was to determine the effect that moderate levels of $CO_2$ (1500 and 3000 ppm, specifically), frequently found in conventional vehicles, have on the psychophysiological state and performance of drivers. Within this goal, a more specific goal was to analyze the possible modulatory influence that the driving time and drivers' cognitive load have on the effects of $CO_2$. This second objective was included to address the hypothesis raised in the literature that the effects of $CO_2$ might become evident or stronger with longer exposure times and when the cognitive load is higher.

## 4.1 Research Questions

Three main research questions were address in this project. These are presented below along with our hypotheses:

1. Do moderate-high levels of $CO_2$ (i.e., 1500 and 3000 ppm) affect the driver's subjective, physiological and cognitive state as compared to normal indoor levels (i.e., 700 ppm)?

Hypothesis: Sleepiness symptoms will increase as a function of $CO_2$ levels, as reflected in the subjective (i.e., Karolinska Sleepiness Scale) and objective measurements (e.g., slower heart rate, greater heart rate variability and worse scores in cognitive tasks).

2. Do these effects translate into a worse driving performance? (e.g., worse longitudinal and/or lateral vehicle control)

Hypothesis: with higher $CO_2$ levels, drivers will show a lower control of the vehicle (e.g., higher speed and lateral position variability).

3. Are $CO_2$ effects on driver performance more evident when driving demands are higher?

Hypothesis: The $CO_2$ effects on driver state and performance will be exacerbated by the driving time (the more time, the stronger the effects) and drivers’ cognitive load (stronger effects while driving and performing an additional task).

## 4.2 Method

To address the different research questions, a study was designed where a group of thirty-two adult drivers performed various cognitive and simulated driving tasks inside a tent specifically built to manipulate $CO_2$ concentration. During the driving, the drivers' ocular and heart activity was recorded. The study was conducted on the premises of VTI in Linköping (Sweden).

*Participants*

Thirty-two volunteer participants (16 men and 16 women) with a mean age of 40.6 and a range of 27-56 years were recruited for the present study. To be eligible, participants had to meet the following inclusion criteria:

- Age between 25 and 60 years
- ≥ 5 years with a driving license
- Body Mass Index < 30
- No current or previous neurological/psychiatric conditions
- No health problems sensitive to elevated $CO_2$ levels (e.g., pregnancy, obesity, respiratory problems), f) no motion sickness, and g) no claustrophobia.

In addition, before attending the experimental sessions, participants were required:

- To sleep more than 6 hours the night before.
- Avoid alcohol consumption 48 hours before the visit.
- Avoid consumption of caffeine or other stimulants on the day of the visit.

*Environmental chamber*

For this study, a plastic tent with a total volume of approximately 24 $m^3$ was built (see Figure 1). Inside the tent were the driving simulator, a computer for cognitive testing and a resting area (i.e., a chair and a table). Inside the tent, pure $CO_2$ mixed with fresh air was injected through a distributor connected to the roof of the tent. Through a mesh and a ventilator located in the ceiling, the $CO_2$ concentration was uniformized throughout the tent. Three $CO_2$ sensors located in the ceiling connected to a closed-loop control system allowed the $CO_2$ level inside the tent to be constantly monitored and regulated automatically and immediately. The fresh air fan was also controlled by the ventilation system controller with a flow rate of approximately 5 m3/min when the environment changed and 1 m3/min during the exhibition. This configuration is supposed to guarantee always fresh air inside the tent and to keep the $CO_2$ concentration as the only variable parameter of the air quality.

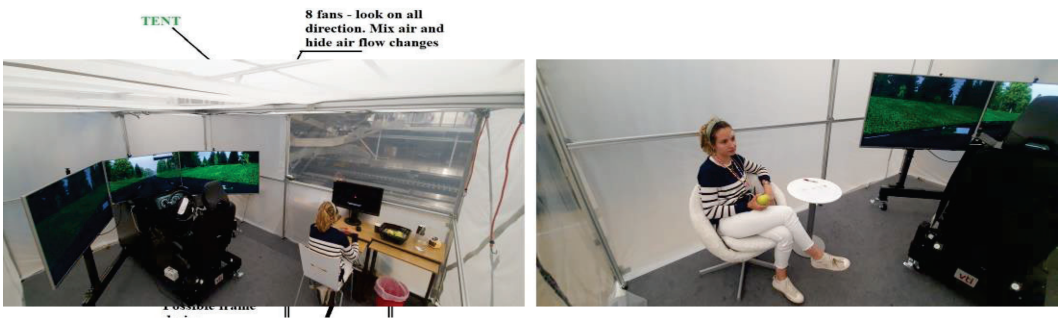


*Figure 2. Driving simulator, cognitive testing and rest areas in the tent.*

*Figure 1. Tent with closed loop control of CO2-concentration*

*Simulator*

The driving task was carried out on a fixed-base simulator located at VTI, Linkoping office (see Figure 2). The simulator consisted of a steering wheel, a car seat, an instrument panel and an automatic gearbox. A rural road with two lanes, one in each direction and a speed limit of 80 km/h, was used as the driving scenario. The driving took place in daylight conditions with low traffic density. Participants did not encounter any vehicles within their lane. Each drive lasted 40 minutes. As driving performance indicators, longitudinal and lateral control measures were recorded (see Table 1).

In the first or second half of the driving time, drivers' cognitive load was increased by activating a simultaneous auditory task. Specifically, the auditory 1-back task was used. Through headphones, the participants listened to a sequence of numbers between 0 and 9, randomly presented in fixed 1.5-second intervals. Their task was to press a button attached to their index finger against the steering wheel as soon as a number was repeated. The performance of this task was not included in the analyses.

*Cognitive tests*

Under different $CO_2$ levels, participants performed two cognitive tests on a computer using the Psychology Experiment Building Language (PEBL, Mueller, 2010) program:

- Psychomotor Vigilance Task (PVT). This task was administered to assess participants' vigilant attention, i.e., the ability to sustain prolonged attention in low-stimulation situations. At 2-10 second intervals, a red circle was presented in the centre of the screen. The task of the participants was to respond to this stimulus as quickly as possible by pressing the left mouse button. The duration of the task was 5 minutes. As a performance indicator, the average response time was calculated. Responses longer than 500 milliseconds were excluded from this calculation.

- Go/no-go task. This task was administered to assess the effects of different $CO_2$ levels on participants' response inhibition ability. Participants were shown a 2x2 grid where every 2 seconds, a "go" or "no go" stimulus was presented on one of the grids for 1 second. The task was to respond to the "go" stimulus as soon as possible by pressing the left mouse button and not to respond when the "no go" stimulus appeared. The presentation rate was 80% for the former and 20% for the latter. Participants performed two blocks. In the first, the letter “P” was the “go” stimulus, whearas the letter “R” was the “no-go” stimulus. In the second block, the stimuli were switched.

*Figure 3. Go/no-go task.*

*Subjective and physiological alertness*

To assess subjective sleepiness during driving sessions, the Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990) was used. During driving, the message "Sleepy?" was displayed at the centre of the driving screen every five minutes. Participants were then asked to verbally indicate their subjective level of sleepiness aloud using the KSS scale (1 - extremely alert, 2 - very alert, 3 - alert, 4 -

fairly alert, 5 - neither alert nor sleepy, 6 - some signs of sleepiness, 7 - sleepy, no effort to stay awake, 8 - sleepy, some effort to stay awake, and 9 - very sleepy, great effort to stay awake, struggling with sleep).

Measurements of heart and ocular activity recorded via a Vitaport 2 amplifier (Temec Instruments BV, The Netherlands) were used as indicators of physiological alertness. In the electrocardiographic recording (ECG), R-peaks were detected, and RR intervals that deviated from the mean of surrounding RR intervals by more than 30% were removed (Karlsson et al., 2012). This allowed the calculation of the interbeat interval, or IBI, which was used as an indicator of heart rate (the higher the IBI, the lower the heart rate). Similarly, heart rate variability was quantified as the root mean square of successive differences (RMSSD) between normal beats; lower heart rate and higher variability have been associated with higher levels of sleepiness (Ahlström et al., 2021; Buendia et al., 2019). In turn, the duration and frequency of blinks served as indicators of participants' level of alertness. Specifically, increased blink frequency and duration have been associated with sleepiness. Using the algorithm of Jammes et al. (2008) , individual blinks were extracted from the electrooculogram (EOG) signal. The interval between half the amplitude of the rise and fall of each blink was used to calculate their duration.

The different physiological parameters analyzed (i.e., IBI, RMSSD, blink frequency and duration) were calculated for each of the 5-min blocks during driving.

*Figure 4. Set-up of ocular and heart activity electrodes*

*Table 1. List of measurements collected*

| Category | Dependent Measurement | Description |
|---|---|---|
| **Driving performance** | Mean speed | Average speed (km/h) |
| | Speed variability | Standard deviation of speed |
| | Lateral position | Mean position in the lane |
| | Variability of the lateral position | Standard deviation of lateral position |
| | SRR0.1 | Frequency of steerings up to 0.1º |

| | | |
|---|---|---|
| | Line crossings (#/5-min) | Number of times one of the wheels crossed the lane lines per 5-min block |
| **Subjective and objective sleepiness** | KSS | Karolinska Sleepiness Scale (1-9) |
| | IBI (Heart rate) | Inter-beat Interval (IBI) |
| | RMSSD (Heart rate variability) | Root mean square of successive differences between normal heartbeats |
| | Blink duration (s) | Mean blink durations |
| | Frequency of long blinks | Number of blinks > 150 ms every 5-min block |
| | Blink frequency | Number of blinks per minute |
| **Cognitive tests** | PVT rt | Response times in Psychomotor Vigilance Test |
| | Go/no-go rt | Response times in Go/no-go task |
| | Go/no-go accuracy | Correct clicks on "go" trials and no-clicks on "no-go" trials. |

*Design and procedure*

A 3 x 2 within-subjects design was used for this study. The independent factors were $CO_2$ level (700 ppm, 1500 ppm and 3000 ppm) and cognitive load (with or without n-back task). In addition, eight 5-min blocks were extracted from each drive (each 40 min) to account for the effects of driving time. Participants completed two experimental sessions on two separate days. In each session, they were exposed to the baseline condition (700 ppm) and one of the experimental conditions (1500 ppm or 3000 ppm). The order was counterbalanced between participants to control for possible learning or mental fatigue effects. Participants and test leaders were blind to the $CO_2$ concentrations.

Before coming to VTI for the first time, all participants received information about the aims of the study and the tasks to be performed. Once at VTI, participants signed an informed consent form and filled out a demographic questionnaire. After fitting the electrodes to assess cardiac and ocular activity, participants entered the tent where they were pre-exposed for 45 minutes. Then,, they performed the two cognitive tasks and the driving task. After completion of the first condition, participants were invited to leave the tent and rest for 5-10 minutes in a separate room. During this time, the $CO_2$ level inside the tent was modified. Participants were then guided back into the tent to perform the next experimental condition. The total duration of the experimental session was 4 hours. Figure 5 shows the experimental procedure in the first session.

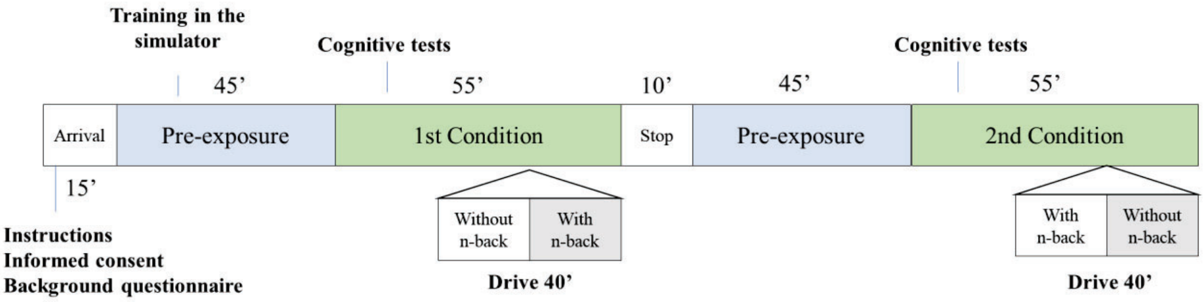


*Figure 5. Procedure in the first experimental session*

# 5 Goals

The main aim of this project was to shed light on a potential mechanism affecting the driver's state, a condition that is known to be a major contributor to traffic accidents (e.g., sleepiness or fatigue). Particularly, the role of $CO_2$ as a risk factor for driver state and performance was evaluated. Complementary to this goal, this project also investigated the modulatory role of cognitive load and driving time on the potential $CO_2$ effects on drivers. The findings were also aimed at providing recommendations to Senseair (partner in the project) for the calibration of future $CO_2$ sensors capable of detecting sub-optimal concentrations inside vehicles.

# 6 Results and goals achievement

## 6.1 Effects on cognitive tests

Although inconsistently, several studies in controlled and ecological settings have reported effects of moderate $CO_2$ levels on cognitive performance as assessed by standardized tests. Based on these results, we hypothesized that participants' cognitive test scores would worsen as $CO_2$ levels increased.

Our analyses reported that the performance on the PVT and go/no-go tasks were similar under different $CO_2$ levels. In general, participants obtained very high levels of accuracy in go/no-go and very similar reaction times in all conditions (see Figure 6).

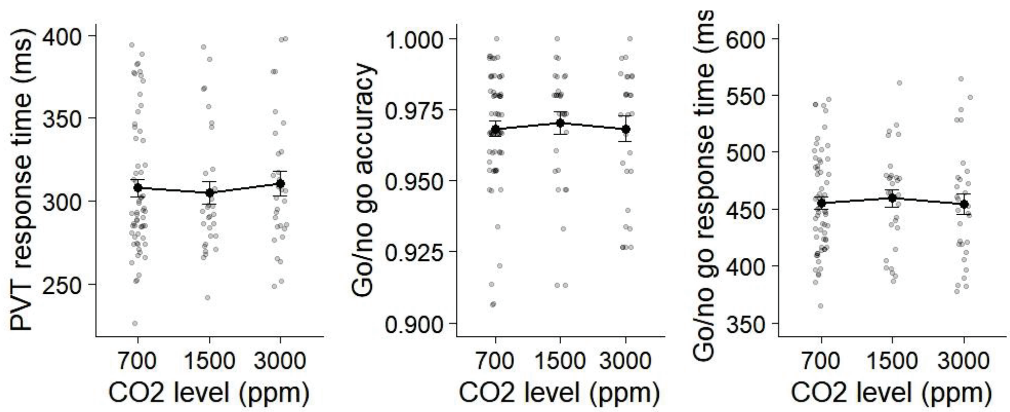


*Figure 6. PVT and Go/no-go scores*

These results are contrary to our hypothesis, based on previous studies. On the one hand, these results might indicate that the cognitive effects of $CO_2$ do not include functions such as attentional vigilance (PVT) or inhibitory control (go/no-go). However, it should not be ruled out that a ceiling effect may have occurred, where the low task difficulty allowed participants to perform the task very well, even under $CO_2$ effects. As indicated by Du et al., (2020) in their review, the most consistent results on the $CO_2$ effects come from studies that used tasks of higher complexity and especially that assessed decision-making processes. On this basis, it seems relevant that future studies use tasks that are more sensitive to the subtle effects of $CO_2$, for example, by increasing the difficulty of standardized cognitive tasks (e.g., by increasing task duration or the number of stimuli).

## 6.2 Effects on subjective and objective alertness

Several studies suggest that moderate $CO_2$ levels decrease occupants' alertness, reflected both subjectively and objectively. In the latter case, changes in the physiological state compatible with increased sleepiness have been reported (Bloch-Salisbury et al., 2000; Snow et al., 2019; Xia et al., 2020a). On this basis, we hypothesized that, with higher the $CO_2$ level in the tent, subjective sleepiness, blink durations and frequency of long blinks would increase, whereas heart activity would decrease (i.e., higher IBI and higher RMSSD).

Overall, our analyses showed mixed results. On the one hand, an increase in the level of subjective sleepiness was observed, although only in the 1500 ppm condition. However, it should be noted that this increment was small, going from a mean score of 5 ("neither alert nor sleepy") to a score of no more than 6 on the KSS (equivalent to "some signs of sleepiness"). Ocular activity, on the other hand, reflected increased sleepiness in the 1500 and 3000 ppm conditions. In particular, the duration of blinks and the number of long blinks (>150 ms) increased in these conditions compared to the baseline condition. Interestingly, we would have expected a decrease in cardiac activity, which is a physiological indicator of sleepiness. Instead, we found increases in cardiac activity in the 1500 ppm condition, and similar rates and rate variability in the 700 and 3000 ppm conditions. Values for all measurements in all conditions can be seen in Figure 7.

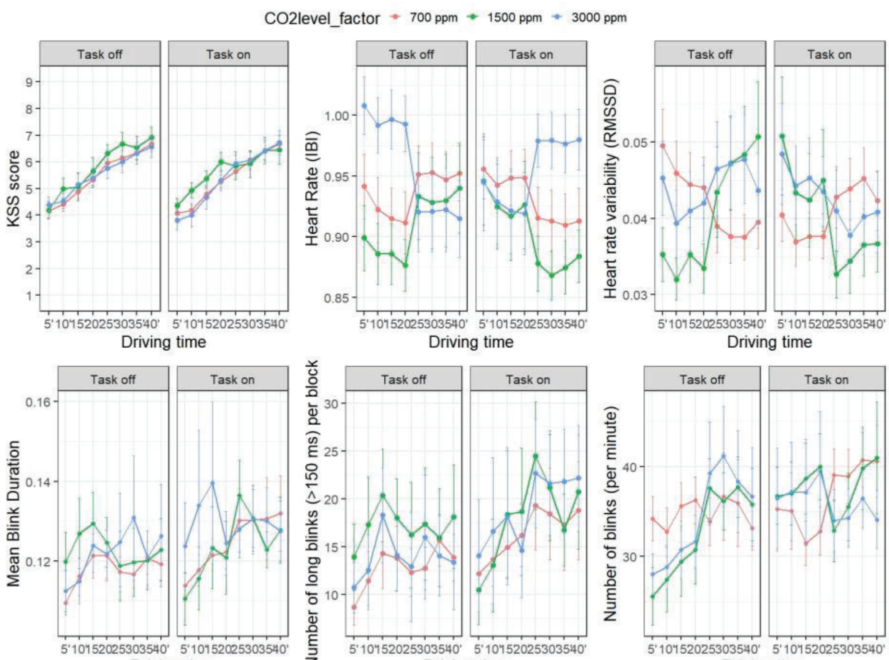


*Figure 7. Indicators for subjective and objective sleepiness*

Based on our results, there are subjective and objective indicators of $CO_2$-induced sleepiness effects. However, these effects are relatively small in size and are most evident in the 1500 ppm condition. This does not support our hypothesis that sleepiness level would increase as a function of the $CO_2$ level. Moreover, there is a discordance between the subjective and ocular measures, which indicate greater sleepiness, and the cardiac measure, which indicates greater physiological activation. This could be explained by the fact that, cardiac activity often increases in response to $CO_2$ exposures as a way to compensate the lower proportion of blood oxygen (Snow et al., 2019; Xia et al., 2020). In our study, however, it is unclear why this mechanism was only activated during the 1500 ppm condition.

## 6.3 Effects on driving performance

The literature on the effects of $CO_2$ on driving performance is practically non-existent. Therefore, our hypothesis was based on performance detriments detected in other environments (e.g., schools, offices or simulated flights). Specifically, we expected to find worse vehicle longitudinal (i.e., higher speed variability) and lateral control performance (i.e., higher variability of lateral position, higher frequency of microsteerings and higher number of line crossings) at higher $CO_2$ levels. As seen in other work, these indicators are sensitive to altered driver states.

Statistical analyses revealed negative effects of $CO_2$ on vehicle control in the 1500 ppm condition. Performance in the 700 and 3000 ppm conditions was similar for most measurements. Furthermore, when the auditory task was active, speed variability increased in the 1500 ppm condition but decrased in the 700 ppm condition. Another interaction effect was also observed where, the addition of the auditory task, reduced the frequency of microsteerings only in the 3000 ppm condition (see detailed results in Figure 8).

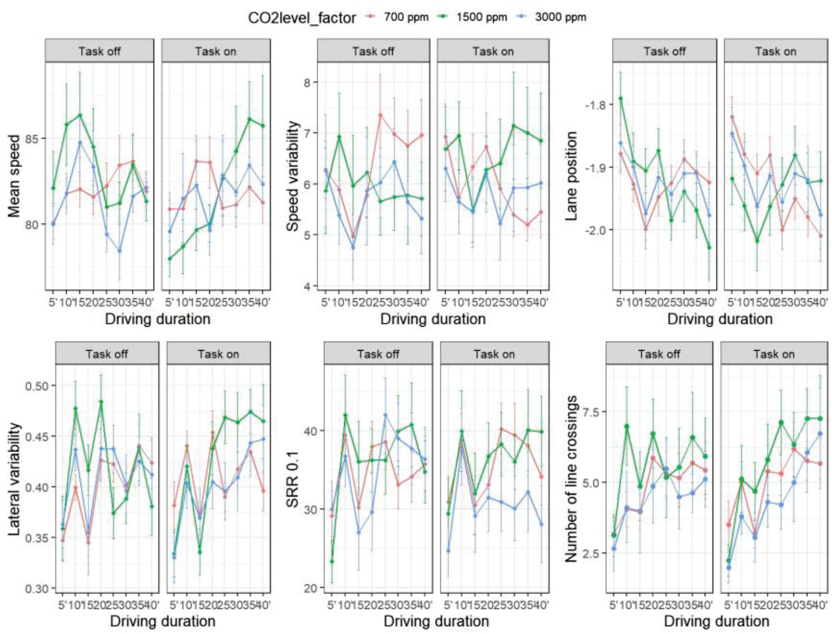


*Figure 8. Driving performance indicators*

Overall, these results show a similar non-linear pattern as that observed in the sleepiness measures, with significant deviations in the 1500 ppm condition and similar values in the other two conditions. Again, no clear explanation can be drawn from the registered measurements. As mentioned earlier, unknown compensatory mechanisms activated at higher concentratinos would explain the better performances in the 3000 ppm condition. Moreover, our obsevations do not support our expectations that stronger $CO_2$ effects on performance would be visible when cognitive load was higher, i.e., when the auditory task was added. By contrast, the addition of the task improved the driving performance under 700 and 3000 ppm conditions and worsened it under 1500 ppm. Finally, it should be noted that the effect sizes found in most effects, although significant, were small. This suggests that the effects of $CO_2$ on lateral and longitudinal vehicle control would likely be smaller than that from other relevant factors analysed in this project, such as the driving time.

## 6.4 Air Quality Perception

In this project, no hypotheses on participants' perception of air quality under different $CO_2$ levels were explicitly established. Despite this, we explored whether our participants were aware of the changes in the concentrations, and if so, whether that influenced their behaviour. Every time the participants got into the tent, they were asked to compare the air quality inside and outside the tent (where the average $CO_2$ level was 450 ppm) by using the following scale: 1 - Much worse, 2 - Worse, 3 - Slightly worse, 4 - Similar, 5 - Slightly better, 6 - Better and 7 - Much better.

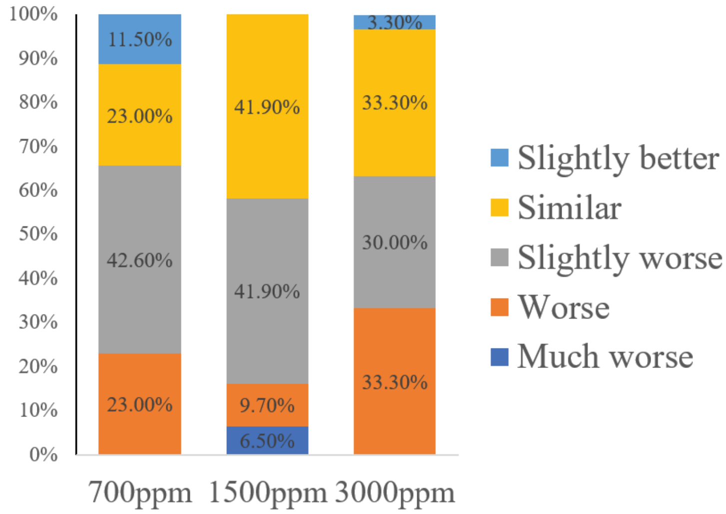


*Figure 9. Distribution of responses to the question on air quality per $CO_2$ condition. No one replied better or much better air quality inside the tent as compared to outside.*

As can be seen in Figure 9, no participant rated the air inside the tent as "better" or "much better" than outside.  This may be partly due to the fact that the lowest concentration inside the tent (700 ppm) was higher than the outside tent concentration (around 450 ppm). In addition, we found a similar distribution of the responses across the $CO_2$ levels. In other words, we did not see a progressive increment in the number of "worse" and "much worse" responses in the 1500 and 3000 ppm. This suggest that participants were likely unaware of the changes in $CO_2$ concentrations inside the tent.

## 6.5 Contribution to the FFI's objectives

The objectives of this project are closely aligned with two aims stated in the Traffic Safety and Automated Vehicles Programme A:

One of them is "to promote development in traffic safety, a better understanding of why incidents and accidents occur is necessary (...)". Specifically, this project has sought to investigate whether driver fitness, essential for safe driving, is affected by an increase in $CO_2$ inside the cabin. The effects of $CO_2$ on humans have been demonstrated in other work, but this project is the first to shed light on its effects on the driver and its implications for traffic safety.In addition, this project has highlighted new lines of research to be considered in future studies looking into the effects of $CO_2$ on drivers.

A more general goal of this project was to provide recommendations for the development of future in-cabin $CO_2$ sensors to detect suboptimal concentrations for driver fitness. This is in line with the need for developing new systems to improve traffic safety, also highlighted in the Roadmap for Traffic Safety and Automated Vehicles Programme A. This goal,however, has not been fully achieved in this project.

The mixed results found in our study did not allow us to define a clear CO2 threshold above which performance problems may occur. Instead, we found indications that performance may fluctuate in the moderate-to-high concentration range.

## 6.6 Dissemination of knowledge and results

| Hur har/planeras projektresultatet att användas och spridas? | Markera med X | Kommentar |
|---|---|---|
| Öka kunskapen inom området | X | This project has provided the first evidence on the role of in-cabin $CO_2$ on driver state and performance. |
| Föras vidare till andra avancerade tekniska utvecklingsprojekt | | |
| Föras vidare till produktutvecklingsprojekt | | |
| Introduceras på marknaden | | |
| Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut | | |

## 6.7 Publications

The following publications are planned:

- Peer-reviewed scientific journal: **Solís-Marcos, I., Hummelgård, C., Gaynullin, B., Thom, S. and Rödjegård, H. (submitted). In-vehicle $CO_2$ effects on driver state and performance. Human Factors.** This work was submitted in April 2022 and is expected to be published in the same year.

- Technical Report at VTI: **Solís-Marcos, I., Hummelgård, C., Rödjegård, H. (in progress). Effects of moderate-high $CO_2$ concentrations on driver state and performance. Technical Report.** This work is in progress and is expected to be published on VTI's website during 2022.

- Pre-print of the scientific paper: **Solís-Marcos, I., Hummelgård, C., Gaynullin, B., Thom, S. and Rödjegård, H. (to be submitted). $CO_2$ effects on driver state and performance. PsyArxiv.** This pre-print version of the scientific article will be submitted to an open-access server.

# 7 Conclusions and future research

The aim of this project was to determine the role that moderate-high $CO_2$ levels have on driver fitness and performance, and whether this is exacerbated by other factors such as cognitive load or driving time. Overall, the results seem to indicate that moderate-high levels of $CO_2$ may affect driver fitness and performance. However, these effects need to be qualified and confirmed in future work.

First, our results show that the effects of $CO_2$ on driver fitness and performance may not follow a dose-response pattern where higher levels generate stronger effects. Surprisingly, we found that intermediate levels (1500 ppm) generated stronger effects. Although not impossible, these results are unlikely explained by inter-individual differences and fatigue or learning effects. As described, a within-subjects design was used where all conditions were counterbalanced to avoid time-related effects. Other studies have reported non-linear $CO_2$ effects where performance problems generated by intermediate levels did not worsen or even improve with further increases in concentrations. In line with these studies, our results reinforce the hypothesis that the $CO_2$ effects on human fitness and performance are complex and probably modulated by other parallel ill-defined cognitive or physiological responses to $CO_2$. The recommendation of this project is that future work should consider these mechanisms in studies in order to provide a better understanding of the effects of $CO_2$ on humans, and on drivers in particular.

Secondly, it should be noted that most of the observed effects are small. For example, the variability of the lateral position of the vehicle, although statistically significant, was only about 4-5 centimetres. Increases in cardiac activity were also very small, and the level of subjective sleepiness increased by about 1 point on the KSS scale. Based on this, it is not expected that $CO_2$, at the concentrations investigated and in the driving scenario analyzed here, would cause significant problems for driving. One hypothesis we put forward is that the effects of $CO_2$ might have been greater in more demanding driving scenarios. An example would be driving in urban spaces where different road users (e.g., cyclists, pedestrians, other vehicles) interact, and where drivers need to attend to different traffic regulations (e.g., speed signs, traffic lights). This hypothesis is supported by observations from a recent review where the most consistent $CO_2$ effects on performance have been in more demanding tasks assessing high-level cognitive functions, such as decision-making. Future studies should investigate whether $CO_2$ concentrations frequently found inside vehicles affect driver performance in such scenarios.

# 8 Partners and contact persons

VTI was the coordinator of the project. The contact person is Ignacio Solís Marcos, Human Factors researcher at the Unit of Humans in the Transport System at VTI (Ignacio.solis@vti.se)

Senseair was the partners in the project. The contact person is Christine Hummelgård, research scientist at Senseair (christine.hummelgard@senseair.com)

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