

ANALYSIS OF THE IMPACT OF AMBIENT PRESSURE VARIATIONS ON THE HEALTH OF DRIVERS AND PASSENGERS IN ROAD TRANSPORT

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ABSTRACT

This article addresses the problematic, yet frequently occurring, fluctuations in atmospheric pressure to which users of modern transport are exposed. These fluctuations occur, among other things, during passages through tunnels, on mountain routes, and as a result of HVAC systems and the structural properties of vehicle cabins. Exposure is caused by substances other than the effects of exhaust emissions or hyperbaric conditions, which may include substances originating from the respiratory system, respiratory system, and nervous system. Their repetitive nature, particularly in the work of professional drivers, can generate discomfort, headaches, disturbances, or side effects, which impact road safety. The paper also includes conclusions regarding the design of cabins and systems, as well as driver work organization, which can contribute to reducing the impact of these phenomena.

Keywords: road transport, safety, management, health, pressure, hyperbaric conditions.

ARTICLE INFO

PolHypRes 2025 Vol. 93 Issue 4 pp. 19 – 30

ISSN: 1734-7009 **eISSN:** 2084-0535

DOI: 10.2478/phr-2025-0022

Pages: 12, figures: 3, tables: 0

page www of the periodical: www.phr.net.pl

Review article

Submission date: 12.08.2025 r.

Acceptance for print: 17.09.2025 r.

Publisher

Polish Hyperbaric Medicine and Technology Society



INTRODUCTION

Modern road transport operates under diverse environmental conditions that influence both the comfort and safety of road users. Vehicles travel through densely built urban areas, mountainous regions, and tunnels [1], where drivers and passengers may experience subtle yet repetitive fluctuations in ambient pressure. These variations stem from atmospheric factors as well as vehicle-specific construction features, including the operation of ventilation and air-conditioning systems or cabin sealing.

Although aviation, hyperbaric, and space medicine extensively describe human physiological responses to significant pressure differences, the minor yet frequently occurring fluctuations typical of road transport have received comparatively little scientific attention. Despite being far milder, their chronic nature—particularly in the case of professional drivers—may have relevant physiological and psychophysiological implications.

Pressure variations occur, among others, during passage through long tunnels [2,3], when traversing mountain routes, due to HVAC system operation, or in truck cabins with limited air exchange. Although often unnoticed, these fluctuations can affect the respiratory and cardiovascular systems, intracranial pressure, and the vestibular apparatus, generating symptoms such as ear discomfort, headaches, or reduced concentration.

From a long-term perspective, even minor fluctuations in pressure may influence physiological load and the ability to maintain alertness, which has potential implications for road safety. Existing research gaps highlight the need for a deeper analysis of micro-pressure fluctuations and their impact on the health of drivers and passengers.

PURPOSE

The purpose of this article is to analyse the impact of ambient pressure variations—both atmospheric pressure and micro-pressure generated within the vehicle cabin—on the health, comfort, and overall psychophysical performance of drivers and passengers in road transport. The study aims not only to identify potential physiological and environmental mechanisms responsible for human responses to pressure fluctuations but also to recognise possible short- and long-term effects on the respiratory, cardiovascular, and auditory systems, the nervous system, and the general well-being of vehicle occupants.

The article seeks to determine to what extent even minor yet repetitive pressure variations may influence stimulus perception, concentration capacity, fatigue levels, reaction speed, and driving comfort, and thereby—indirectly—road safety. The analysis includes a review of available literature, including clinical and engineering studies, a comparison with conditions typical of modern road transport, and the identification of research gaps in the domain of micro-pressure fluctuations inside vehicles.

Additionally, the objective of this article is to formulate practical conclusions and recommendations regarding cabin design, ventilation and air-conditioning systems, and driver work organisation in ways that minimise the negative effects of pressure variations on the human organism. The study also aims to establish

a foundation for further empirical research to deepen the understanding of relationships between the vehicle microclimate and the health and safety of road users.

DISCUSSION

The influence of ambient pressure on the health of travellers and drivers is characterised by substantial variability and is largely determined by both the specific mode of transport and the dynamics with which this environmental parameter changes. While in road and rail transport such effects are typically of secondary importance, they become crucial from a physiological standpoint in aviation and in transportation conducted at high altitudes.

In aviation, atmospheric pressure variability represents one of the most thoroughly examined and physiologically significant factors associated with travel safety. Passenger aircraft cabins, although pressurised, are intentionally maintained at a pressure equivalent to an altitude of approximately 1,500 to 2,500 metres above sea level. The lowered atmospheric pressure induces two key mechanisms affecting the human body.

The first is **hypobaric hypoxia**, resulting from a reduction in the partial pressure of oxygen (pO_2). This leads to decreased haemoglobin saturation and, consequently, potential tissue hypoxia. In healthy individuals, this manifests primarily as fatigue [4], headaches, and diminished cognitive performance, including impaired concentration and memory function. Individuals suffering from respiratory diseases—such as chronic obstructive pulmonary disease or severe asthma—as well as patients with cardiovascular diseases [5], including heart failure or angina pectoris, are particularly vulnerable. Their limited compensatory capacity increases the risk of exacerbations and acute incidents.

The second important phenomenon is barotrauma, a pressure-related injury governed by Boyle's law, according to which pressure reduction leads to expansion of gases trapped within closed bodily cavities. This most commonly affects the middle ear and paranasal sinuses, where insufficient patency or dysfunction of the Eustachian tubes may result in pain, a sensation of fullness, or, in severe cases, tympanic membrane rupture. Similar effects may occur in the gastrointestinal tract, where expanding intestinal gases can cause bloating, discomfort, or pain. These effects will be addressed in the later stages of this study; however, the present article focuses primarily on hypobaric hypoxia in the context of road transport.

In road and rail transport, atmospheric pressure fluctuations are generally slow and small in magnitude, rarely producing physiological effects comparable to those observed in aviation. Nevertheless, in certain specific circumstances, they may constitute a significant environmental factor. Such situations include travel through high mountain regions, where rapid increases in altitude—particularly above 2,500 metres—may induce mild altitude sickness in drivers and passengers, most commonly manifested by headaches and nausea.

By contrast, in high-speed rail systems, which operate at velocities exceeding 200 km/h, rapid pressure changes can occur during tunnel entry [4,6]. These changes produce significant pressure differentials between the train interior and the external environment,

potentially causing discomfort or even increasing the risk of ear barotrauma. For this reason, modern trains are equipped with pressurisation systems and structural solutions that mitigate sudden pressure variations.

Within the scientific literature on health in transport, several primary research domains can be distinguished. Studies in aviation medicine focus predominantly on barotrauma, providing detailed descriptions of physiological responses to pressure changes and offering preventive and therapeutic recommendations, particularly concerning individuals with respiratory or cardiovascular disorders.

These studies emphasise the importance of adequate cabin pressurisation and the targeted use of supplemental oxygen when necessary.

In contrast, research concerning road transport [7] is dominated by epidemiological and environmental analyses, which indicate that although pressure variations associated with weather fronts may affect meteorosensitive individuals—exacerbating joint pain, migraines, or similar ailments—they do not represent a primary health risk for drivers. Far more significant risk factors include chronic exposure to air pollutants such as nitrogen oxides and particulate matter. This is especially relevant for professional drivers and correlates with increased incidence of cardiovascular diseases, hypertension, and respiratory disorders.

Equally important are psychophysiological factors, as numerous studies highlight that chronic stress, irregular working hours, and disturbed circadian rhythms are among the key determinants of hypertension and other cardiovascular conditions within this occupational group.

HYPOBARIC HYPOXIA AND ROAD TRANSPORT

Hypobaric hypoxia is a condition resulting from a decrease in the partial pressure of oxygen in the air, which accompanies the reduction of atmospheric pressure as altitude increases. This phenomenon is well documented in high-altitude and aviation medicine, as well as in research on human adaptation to extreme environmental conditions. However, in the context of road transport, hypobaric hypoxia is not typically regarded as a physiological burden for drivers and passengers, despite the fact that driving through mountainous regions may induce gradual or abrupt pressure changes that affect oxygen availability in the body.

As altitude rises, atmospheric pressure decreases and, consequently, the partial pressure of oxygen (pO_2) declines, reducing the diffusion gradient that drives oxygen transfer from the alveoli into the bloodstream. Although the degree of hypoxia experienced on mountain roads is significantly milder than that encountered in high-altitude or aviation conditions, it may still produce noticeable physiological effects in individuals who are particularly sensitive, suffer from cardiovascular or respiratory diseases, or cover long distances in variable terrain.

The most commonly reported consequences of mild hypobaric hypoxia include:

- increased respiratory and heart rates as a compensatory response to reduced blood oxygen saturation,
- impaired visual acuity and stimulus perception, particularly during rapid transitions across altitude levels,

- diminished psychomotor performance, including prolonged reaction time and reduced concentration,
- heightened fatigue and drowsiness resulting from decreased cerebral oxygenation,
- headaches and a sensation of pressure in the sinuses and ears, caused by combined changes in pressure and tissue oxygenation.

In road transport, this phenomenon may be particularly relevant when travelling along routes with substantial elevation differences, such as in the Alpine or Carpathian regions, where drivers ascend or descend large altitude changes within short time intervals. The body's compensatory mechanisms may act with a delay, meaning that even small declines in pO_2 can temporarily affect cognitive functions, risk perception, and the ability to accurately assess traffic situations.

It should also be noted that modern vehicle cabins, although not hermetically sealed like aircraft cabins, nonetheless exhibit certain features of partial isolation from the external environment. Air-conditioning, ventilation, and filtration systems influence the interior microclimate, and in specific conditions—such as high HVAC load, rapid cabin cooling, or limited airflow—they may temporarily reduce effective air exchange. In such circumstances, subjective symptoms of mild hypoxia may intensify, particularly during prolonged driving.

From a road-safety perspective, it is important to recognise that even mild hypobaric hypoxia can affect cognitive functions essential for vehicle operation, including alertness, reaction speed, motor control, decision-making processes, and visuomotor coordination. Under conditions of sustained psychophysical strain—typical for professional drivers—this may contribute to an increased risk of perceptual errors and accidents.

COGNITIVE FUNCTIONS OF THE DRIVER

ALERTNESS (VIGILANCE)

Mild hypoxia impairs the ability to sustain attention and detect unexpected stimuli. A meta-analysis by McKeown et al. demonstrated significant deterioration in attention, memory, processing speed, and executive functions under hypoxic conditions. Simulator studies [8,9] showed that exposure to altitudes $\geq 3,000$ m led to an increased number of missed signals and reduced vigilance (Fig. 1, Fig. 2). Even mild hypoxia—equivalent to altitudes of 2,000–3,000 m—may decrease blood oxygen saturation by 3–5%, resulting in:

- Reduced ability to detect hazards (e.g., pedestrians, sudden braking),
- Increased susceptibility to microsleep and lapses in concentration,
- More errors in tasks requiring continuous attention after only 30–60 minutes of exposure, as observed in simulation studies.

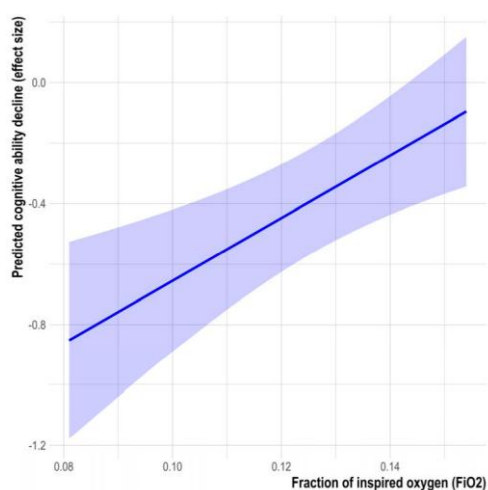


Fig. 1 Predicted cognitive ability decline in hypoxia as a function of severity [8].

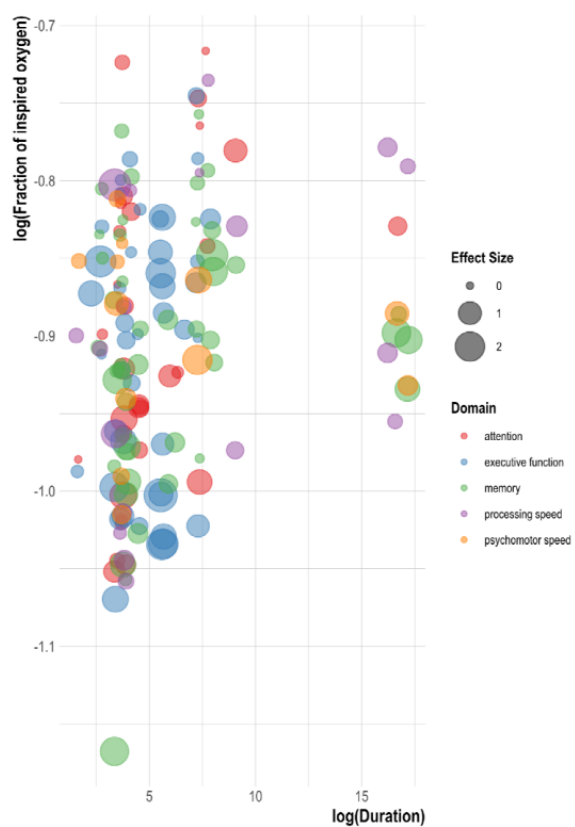


Fig 2. Bubble plot visualising the 151 effect sizes across all domains in relation to the severity and duration of hypoxia exposure. Notably, as fraction of inspired oxygen decreases effect of hypoxia increases for most cognitive domains [10].

REACTION TIME

Reaction time is critical in emergency situations. A 2024 meta-analysis showed that even short-term hypoxia lengthens reaction time and reduces response accuracy, although general attention remained relatively resilient.

A Chinese study (2,800 m vs. control) did not detect significant changes at 2,800 m; however, at 3,600 m and above, reaction performance became significantly slower ($P < 0.05$; at 4,400 m, $P < 0.01$). The effect concerned choice reaction tasks, but not simple reaction time or tapping speed. Hypoxia leads to:

- Prolonged motor and cognitive reaction times (e.g., delayed braking after detecting an obstacle),
- Reduced efficiency in processing visual and auditory stimuli,
- EEG studies indicate a decrease in P300 amplitude, which correlates with slower information processing.

MOTOR CONTROL

Exposure to hypobaria produces difficulties in fine motor control required for precise vehicle handling [10]:

- At an altitude of 3,842 m, decreases in critical flicker fusion frequency (CFFF) and cerebral blood flow index were observed, although motor tasks remained largely preserved due to compensatory hemodynamic mechanisms.
- After 48 hours at 3,600 m, increased co-activation of antagonistic muscles (biceps/triceps) was noted, indicating altered motor control and suggesting reduced precision of movement.

DECISION-MAKING PROCESSES

Driving decisions are rapid and multi-factorial. Hypoxia affects them by:

- Increasing impulsivity—drivers are more prone to risky manoeuvres (e.g., overtaking).
- Reducing risk assessment capacity—drivers exhibit difficulty anticipating consequences [11,12].
- Increasing the frequency of speeding and ignoring regulations in experiments involving poikilocapnic hypoxia.
- Influencing loss-related decisions: research showed that under hypoxic conditions participants were more inclined to take risks when potential outcomes involved losses, but not gains [13].

VISUOMOTOR COORDINATION

Visuomotor coordination integrates visual perception with motor responses. Under hypoxia:

- The ability to track moving objects deteriorates (e.g., vehicles in adjacent lanes).
- Errors increase in tasks requiring precise steering.
- Corrective steering responses to rapid changes in road conditions become delayed.

- Studies by Hohenauer et al. [14] comparing normobaric and hypobaric hypoxia revealed that hypobaria impairs cognitive–motor performance even during mild hypoxia, by reducing brain oxygenation and shortening psychomotor reaction times.

PROPOSED SOLUTION

A potential solution applicable to road transport conditions is the implementation of a system that monitors altitude (barometric pressure) and/or passenger blood oxygen saturation (SpO_2). If altitude-related parameters and/or SpO_2 levels begin to indicate a risk of hypoxia, the system supplies a controlled amount of oxygen into the vehicle's air-circulation system (either through direct oxygen infusion or by increasing the oxygen fraction in the air mixture), thereby maintaining safe blood-oxygen saturation levels without creating an excessively oxygen-rich environment that could pose a safety hazard.

Oxygen Injection in a Vehicle Cabin Depending on Altitude

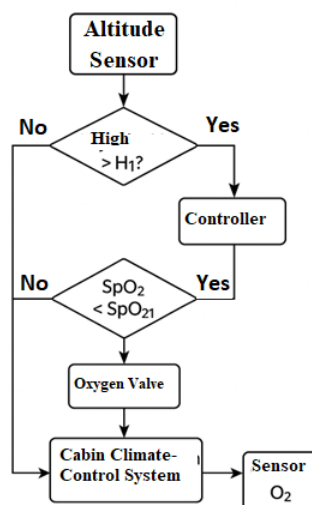


Fig. 3 Diagram of the Oxygen Injection System for the Vehicle Cabin. Source: Author's Own Work.

SYSTEM ACTIVATION TRESHOLDS

- If altitude $< H_1$ (e.g., 1,500 m) and $SpO_2 > 95\%$ → the system remains off / in standby mode.
- If altitude is between H_1 – H_2 (e.g., 1,500–2,500 m) → monitor SpO_2 ; intervene only if SpO_2 drops below the threshold (e.g., 94%).
- If altitude $> H_2$ (e.g., $> 2,500$ – $3,000$ m) → pre-emptively increase FiO_2 moderately (target SpO_2 : 95–97%) if required.

The oxygen-injection system for the vehicle cabin, operating as a function of altitude, relies on continuous monitoring of environmental and physiological parameters, followed by automatic regulation of the amount of oxygen introduced into the vehicle interior. The system is based on an altitude sensor that measures barometric pressure and, on this basis, calculates the current elevation above sea level. As altitude increases, the partial pressure of oxygen decreases, which may lead to reduced blood oxygen saturation in passengers. Once the system detects that the vehicle has exceeded a predefined altitude threshold, it switches to enhanced monitoring mode and analyses SpO_2 levels using pulse oximeters assigned at minimum to the driver and, optionally, to other occupants.

If blood oxygen saturation begins to fall below the programmed safety threshold, the controller initiates an increase in the oxygen concentration within the cabin.

At this stage, an oxygen concentrator or a system supplying oxygen from a compressed source becomes active, and a precision-controlled valve doses the gas into the vehicle's air-distribution system in a regulated amount. The oxygen mixes with the air circulating through the climate-control system, and its concentration is continuously measured by an O_2 sensor installed within the airflow. This enables the controller to maintain oxygen levels sufficient to ensure proper blood oxygen saturation in passengers, while simultaneously preventing excessive oxygen enrichment, which could increase fire risk.

The entire process operates within a closed-feedback loop: increasing altitude triggers enhanced SpO_2 monitoring; a decline in saturation initiates oxygen injection; and the cabin O_2 sensor provides real-

time information on the current concentration, allowing the controller to adjust the flow accordingly. When the vehicle descends to a lower altitude or saturation returns to normal, the system automatically reduces or fully suspends oxygen delivery. As a result, the system operates only when necessary, minimizing energy consumption and mitigating risks associated with oxygen-enriched cabin air.

SUMMARY

In summary, the concept of implementing an oxygen-injection system within a passenger vehicle cabin represents an innovative response to the growing need for physiological safety among drivers and passengers travelling in high-altitude environments. The integration of altitude sensors, saturation monitoring, and automatic oxygen-concentration regulation forms a coherent system capable of significantly reducing the risk of hypoxia and its associated impairments in concentration, reaction time, and motor coordination. When properly designed and equipped with adequate safeguards, such a system could provide meaningful support to the driver, operating unobtrusively in the background and activating only when environmental conditions genuinely require intervention.

From a technical standpoint, this solution necessitates further research and development, including refinement of control algorithms, assessment of the impact of oxygen-enriched air on fire safety and user comfort, and a detailed regulatory analysis, as a system combining medical and automotive functionalities must comply with stringent standards in both domains. Nevertheless, the potential of this concept is evident: when correctly implemented, it could become a valuable measure to enhance road-traffic safety in specific, yet increasingly common, terrain conditions.

Thus, it represents a compelling direction for the development of driver-assistance technologies, integrating engineering, medicine, and ergonomics into a unified system whose primary objective is to protect the driver's health and functional capacity.

REFERENCES

1. Miyachi, T., Noguchi, Y., & Yamauchi, Y. (2024). One-dimensional analysis of pressure variations induced by trains passing each other in a tunnel. *Journal of Fluid Mechanics*. Cambridge University Press & Assessment
2. Weng, M., et al. (2023). Influence of the door opening on the pressure transient ... *Tunnelling and Underground Space Technology*.
3. Zhang, J., et al. (2025). A novel asymptotic linear method for micro-pressure wave mitigation ,*Journal of Central South University*.
4. Du, Q., et al. (2025). Field study on pressure fluctuations and comfort analysis ... *Transportation Research Part*.
5. *ILO Encyclopaedia*. (2011). Physiological Effects of Reduced Barometric Pressure.
6. Feng, Z., et al. (2021). Effects of the Spatial Structure Conditions of Urban Underpass on Driver Stress. *International Journal of Environmental Research and Public Health*.
7. Krakowczyk, S., Łazarz, B., Czech, P., Mańka, A., & Matyja, T. *Wpływ warunków drogowych na drgania ogólne odczuwalne w czasie jazdy samochodem osobowym*.
8. Daniel J. McKeown, Douglas J. Angus , Ahmed A. Moustafa, Victor R. Schinazi Hypoxia and Cognitive Ability in Humans: A Systematic Review and MetaAnalysis, Australia 2025.
9. Wentylator H, Meng Y, Zhu L, Wentylator M, Wang DM, Zhao YQ. *Brain Behav*. 2024 luty;14(2):e3418. doi: 10.1002/brb3.3418. A Review of Methods for Assessing Cognitive Function in High-Altitude Hypoxic Environments
10. D. De Bels, C. Pierrakos, A. Bruneteau, F. Reul, Q. Crevecoeur, N. Marrone, D. Vissenaeken, G. Borgers, C. Balestra, P. M. Honoré and S. Theunissen; Variation of Cognitive Function During a Short Stay at Hypobaric Hypoxia Chamber (Altitude: 3842 M), *Frontiers in Physiology*, Belgium 2019.
11. Manivannan, A., Chin, W. C. B., Barrat, A., & Bouffanais, R. (2020). On the Challenges and Potential of Using Barometric Sensors to Track Human Activity. *Sensors*.
12. Miyachi, T., Noguchi, Y., & Yamauchi, Y. (2024). One-dimensional analysis of pressure variations induced by trains passing each other in a tunnel. *Journal of Fluid Mechanics*. Cambridge University Press & Assessment
13. Stefania Pighin, Nicolao Bonini, Łucja Savadori, Constantinos Hadjichristidis, Tommaso Antonetti, Federico Schena, Decision making under hypoxia: Oxygen depletion increases risk seeking for losses but not for gains, *Judgment and Decision Making*, 2012, vol. 7, issue 4, 472-477, 2012
14. Hohenauer E, Freitag L, Costello JT, Williams TB, Ku'ng T, Taube W, et al. (2022) The effects of normobaric and hypobaric hypoxia on cognitive performance and physiological responses: A crossover study. *PLoS ONE* 17(11): e0277364. <https://doi.org/10.1371/journal.pone.0277364> Editor: Shigehiko Ogoh, Tokyo Joshi Ika Daigaku Toyo Igaku Kenkyujo Clinic, JAPAN The effects of normobaric and hypobaric hypoxia on cognitive performance and physiological responses: A crossover study.

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