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EP 79, 4.-5. 10. 1979	(I. jugoslovanski simpozij o elektroniki v prometu)
EP 80, 9.-10. 10. 1980	
EP 85, 10.-11. 10. 1985	
EP 86, 9.-10. 10. 1986	(VII. jugoslovanski simpozij o elektroniki v prometu)
EP 91, 10.-11. 10. 1991	(XIII. jugoslovanski simpozij o elektroniki v prometu)
ISEP 93, 7.-8. 10. 1993	(2. mednarodni simpozij o elektroniki v prometu)
ISEP 94, 6.-7. 10. 1994	(3rd International Symposium on Electronics in Traffic)
ISEP 95, 5.-6. 10. 1995	
ISEP 96, 10.-11. 10. 1996	
ISEP 97, 9.-10. 10. 1997	
ISEP 98, 8.-9. 10. 1998	
ISEP 99, 7.-8. 10. 1999	
ISEP 2001, 4. 10. 2001	
ISEP 2002, 3.-4. 10. 2002	
ISEP 2003, 9.-10. 10. 2003:	INTELLIGENTNI TRANSPORTNI SISTEMI, ITS
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ISEP 2019, 25.-26. 3. 2019:	INTERNET OF THINGS IN INTELLIGENT TRANSPORT SYSTEMS AND SERVICES
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ISEP 2023, 27. 3. 2023	(3rd Virtual event): SMART MOBILITY AND DIGITALISATION OF TRANSPORT
ISEP 2024, 23. 10. 2024:	ITS AND GREEN TRANSPORT
ISEP 2026, 21. 10. 2026	INTELLIGENCE ON THE MOVE

Welcome Letter

Dear Colleagues, Distinguished Guests, and Participants,

It is our great pleasure to welcome you to the 33rd International Symposium on Electronics in Transport: ISEP 2026, held in Portorož, Slovenia, in conjunction with the 17th Slovenian Congress on Transport and Transport Infrastructure (SKoPPI).

Over more than three decades, ISEP has established itself as an important meeting point for researchers, transport professionals, industry representatives, and decision-makers involved in the development and application of intelligent transport systems and services.

In recent years, we have also established something of a tradition: ISEP has found a regular home in Portorož, where we now meet every two years alongside the SKoPPI. This arrangement provides an excellent opportunity to bring together different perspectives on transport, combining advances in digital technologies and intelligent transport systems with broader challenges related to transport infrastructure, planning, management, and mobility.

The theme of this year's symposium, "Intelligence on the Move," reflects the rapid changes taking place in the transport sector. Artificial intelligence, connectivity, automation, and advanced data-driven solutions are increasingly shaping the way we plan, operate, and manage transport systems. These technologies offer considerable opportunities to improve traffic safety, efficiency, sustainability, and the overall quality of mobility. However, technological progress also raises important questions. How can we ensure that increasingly intelligent and automated transport systems remain safe, reliable, and accessible? How can new technologies be effectively integrated into existing infrastructure and operational practices? And perhaps most importantly, how can we ensure that technological innovation serves the actual needs of transport users and society? These are some of the challenges that ISEP 2026 aims to address. Through scientific contributions, professional presentations, and discussions, the symposium provides a platform for exchanging ideas, sharing experiences, and exploring solutions that bridge the gap between research and practical implementation.

We would like to express our sincere gratitude to all authors, reviewers, invited speakers, members of the scientific and organising committees, and supporting organisations for their valuable contributions. Their dedication and expertise are essential to the continued success of ISEP. We hope that the contributions presented in these proceedings will provide useful insights, stimulate further discussion, and encourage new collaborations in the field of intelligent transport systems and services.

We wish all participants a successful and inspiring ISEP 2026 and look forward to continuing our biennial meetings in Portorož!

On behalf of the Organising and Scientific Committees ISEP 2026



Robert Rijavec
President of S-ITS, Slovenian ITS Association

TABLE OF CONTENTS

A regulatory and technological framework for the safe and responsible deployment of advanced automated driving systems Dušan Zalar	P01
Functional safety of road infrastructure to support Connected, Cooperative and Automated Mobility (CCAM) Darko Kokot, Rok Vežočanik	P02
Security architecture of the European C-ITS trust framework Andrej Štern	P03
Potential and effectiveness of diagonal pedestrian crossings in urban areas Žiga Hrovatin, Rok Marsetič	P04
Emotion detection using wearable physiological sensors in traffic safety research Dejan Žagar, Franc Dimc, Marko Golnar, Matija Svetina	P05
Information and data requirements for remote maritime pilotage: a pilot-centred perspective Matej Glišović, Evelin Krmac	P06
The use of unmanned aerial systems in state operations: analysis of legislation and best practices abroad and comparison with the current state in Slovenia Alekselj Majkić, Igor Petrović	P07
Effects of normobaric hypoxic exposure on physiological responses, cognitive performance, and simulated flight performance in general aviation pilots Peter Pipp, Igor Petrović	P08
Design and manufacture of the remote-controlled aircraft Brvinc for the design/build/fly 2026 competition Jakob Erhartič, Igor Petrović	P09

A REGULATORY AND TECHNOLOGICAL FRAMEWORK FOR THE SAFE AND RESPONSIBLE DEPLOYMENT OF ADVANCED AUTOMATED DRIVING SYSTEMS

REGULATIVNI IN TEHNOLOŠKI OKVIR ZA VARNO IN ODGOVORNO UVAJANJE NAPREDNIH ASISTENČNIH SISTEMOV VOŽNJE Z RAZŠIRJENIM OBMOČJEM DELOVANJA

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Abstract

The deployment of advanced driver assistance systems with an extended operational design domain (Extended ODD), the so-called L2++ sub-level, on public road networks represents a technological leap that, due to discrepancies with existing legislative frameworks, generates substantial safety and legal risks. Although these systems operationally perform the entire dynamic driving task (DDT) in complex urban environments, legal liability and the obligation to supervise remain exclusively with the driver. This creates a structural informational and legal asymmetry: manufacturers use the public road network to optimise algorithms, while individual drivers bear all operational risks during system failures. An additional research challenge arises from the lack of sensor redundancy under conditions involving unadapted local infrastructure (infrastructural edge cases) and from the telemetry logging methodology, which frequently fails to classify anomalies as system errors when drivers intervene in time, thereby distorting the real-world assessment of safety risks.

To address the aforementioned challenges, this paper proposes a comprehensive technical and regulatory framework that mandates the implementation of a cloud-based DSSAD (Data Storage System for Automated Driving) back-end infrastructure as a prerequisite for vehicle type approval. The framework is based on the Data Escrow Storage principle, which, in the event of critical kinematic or system-related events, ensures cryptographically verified and standardised logging of parameters via a unified Application Programming Interface (API). Such an approach ensures evidentiary symmetry by shifting the burden of proof regarding software integrity onto manufacturers and enables forensic traceability for independent traffic accident investigations. The proposed back-end system grants infrastructure managers anonymised access to data for the remediation of hazardous road sections, whilst providing recognised scientific institutions with access to data to foster public safety, artificial intelligence development, and scientific transport research.

Keywords

Advanced Driver Assistance Systems (ADAS), Extended Operational Design Domain (ODD), L2++ Automation, Road Safety, Data Storage System for Automated Driving (DSSAD), Data Escrow, Legal Liability, Vehicle Type Approval.

FUNCTIONAL SAFETY OF ROAD INFRASTRUCTURE TO SUPPORT CONNECTED, COOPERATIVE AND AUTOMATED MOBILITY (CCAM)

FUNKCIONALNA VARNOST CESTNE INFRASTRUKTURE PRI PODPORNIM REŠITVAH ZA CCAM MOBILNOST

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Abstract

The goal of the AugmentedCCAM project is to help accelerate the adoption of solutions for cooperative, connected, and automated mobility (CCAM) by developing concepts for physical, digital, and communication (PDI) infrastructure to support CCAM.

Within the project, several concrete use cases from the CCAM driving environment were developed using PDI: giving right of way to an approaching emergency vehicle, protecting vulnerable road users, optimizing traffic management based on vehicle data, determining the location (localization) of various objects and connected vehicles, minimum-risk maneuvering, optimized logistics operations using advanced digital technologies and solutions, integration of vehicles into traffic flow, and driving in areas with temporary roadwork.

To assess the impact of the proposed PDI improvements, a methodology was developed that covers eight different areas of impact. The second area covers the assessment of infrastructure functional safety in relation to autonomous vehicles: the readiness of road infrastructure for CCAM and autonomous driving failures.

The article presents the project and case studies, as well as an example of the use of indicators to support CCAM solutions.

Keywords

CCAM, AugmentedCCAM, autonomous driving, functional safety of infrastructure

Povzetek

Cilj projekta AugmentedCCAM je pripomoči k pospešenemu uvajanju rešitev za kooperativno, povezano in avtomatizirano mobilnost (CCAM), z razvojem konceptov fizične, digitalne in komunikacijske (PDI) infrastrukture za podporo CCAM.

V projektu je bilo s pomočjo PDI razvitih nekaj konkretnih primerov iz voznega okolja CCAM: prednost v prometu bližajočemu se reševalnemu vozilu, zaščita ranljivih udeležencev v prometu, optimizacija upravljanja prometa na podlagi podatkov o vozilih, določanje položaja (lokalizacija) različnih objektov in povezanih vozil, manever minimalnega tveganja, optimizirano logistično poslovanje s pomočjo naprednih digitalnih tehnologij in rešitev, vključevanje vozil v prometni tok, in vožnja v območju začasnih del na cesti.

Za oceno vpliva predlaganih izboljšav PDI je bila ustvarjena metodologija, ki zajema osem različnih področij vpliva. Drugo področje zajema oceno funkcionalne varnosti

infrastrukture v povezavi s samovozečimi vozili: pripravljenost cestne infrastrukture na CCAM in izpad samovoznosti.

V članku so predstavljeni projekt in študijski primeri ter primer uporabe kazalnikov za podporne rešitve CCAM.

Ključne besede

CCAM, AugmentedCCAM, samovoznost, funkcionalna varnost infrastrukture

KOOPERATIVNA, POVEZANA IN AVTOMATIZIRANA MOBILNOST (CCAM)

Kooperativna, povezana in avtomatizirana mobilnost (CCAM) predstavlja evropski pristop k razvoju prihodnjega prometnega sistema, ki združuje sodelovanje med vozili, infrastrukturo in udeleženci v prometu, napredno povezljivost ter avtomatizacijo vožnje. Cilj je zagotoviti varnejšo, učinkovitejšo in okoljsko bolj trajnostno mobilnost po vsej Evropi.

CCAM temelji na neprekinjeni izmenjavi podatkov med vozili, prometno infrastrukturo in upravljavci prometa. Pri tem se uporabljajo informacije o prometni signalizaciji, cestni infrastrukturi, vremenskih in svetlobnih razmerah, stanju vozišča, prometnih tokovih, delih na cesti in okoliških vozilih. Pomembno vlogo imajo tudi napredne digitalne storitve, kot so kooperativni inteligentni transportni sistemi (C-ITS), visokoločljivi zemljevidi, digitalni dvojčki, umetna inteligenca, komunikacijska omrežja, senzorji in obcestne komunikacijske enote [1].

Evropska komisija je leta 2016 sprejela strategijo za uvajanje kooperativnih inteligentnih transportnih sistemov, s katero želi preprečiti razvoj nepovezanih nacionalnih rešitev ter vzpostaviti enoten evropski okvir za povezano mobilnost. Strategija spodbuja interoperabilnost sistemov, raziskave in inovacije, kibernetško varnost, varstvo podatkov ter mednarodno sodelovanje na področju avtomatiziranega prometa.

Za podporo uvajanju CCAM je bilo vzpostavljenih več evropskih pobud. Platforma C-ITS združuje evropske institucije, države članice in industrijo pri oblikovanju

skupnih priporočil za uvajanje povezanih prometnih sistemov. Platforma C-Roads omogoča preizkušanje storitev v realnih prometnih razmerah in zagotavlja njihovo čezmejno interoperabilnost. Platforma za testiranje CCAM pa koordinira raziskovalne dejavnosti, testiranja in pripravo na širšo uporabo avtomatiziranih vozil [1].

Pomemben korak predstavlja tudi Partnerstvo CCAM, ustanovljeno v okviru programa Horizon Europe. Gre za javno-zasebno partnerstvo med Evropsko komisijo in zasebnim sektorjem, ki ga zastopa združenje CCAM Association. Njegov namen je pospešiti razvoj in uvajanje povezanih ter avtomatiziranih prometnih tehnologij v Evropi [2].

Glavni cilji partnerstva so izboljšanje prometne varnosti, zmanjšanje prometnih zastojev, zmanjšanje okoljskih vplivov cestnega prometa, zagotavljanje dostopne mobilnosti za ljudi in blago ter krepitev konkurenčnosti evropske avtomobilske in prometne industrije. Združenje CCAM Association pri tem zastopa industrijo, raziskovalne organizacije in druge deležnike ter sodeluje pri oblikovanju raziskovalnih prioritet in pripravi razpisov programa Horizon Europe [2].

CCAM tako predstavlja celovit okvir za digitalno preobrazbo cestnega prometa, katerega namen je s povezljivostjo, sodelovanjem in avtomatizacijo omogočiti razvoj varnejših, pametnejših in trajnostnih prometnih sistemov prihodnosti. Projekt Augmented CCAM pa je z razvojem konceptov fizične, digitalne in komunikacijske (PDI) infrastrukture testiral nekaj svojevrstnih rešitev za podporo CCAM.

PRISPEVEK PROJEKTA AUGMENTEDCCAM K RAZVOJU CCAM

Vizija prihodnje mobilnosti predvideva, da bodo do leta 2050 vsi udeleženci v prometu medsebojno povezani ter bodo v realnem času izmenjevali podatke o prometnem okolju. Takšna povezanost bo omogočila boljše zaznavanje okoliških razmer, večjo prometno varnost, učinkovitejše upravljanje prometa in doseganje okoljskih ciljev.

Samovozeča in povezana vozila danes za zaznavanje okolice uporabljajo različne senzorje, katerih delovanje omejujeta doseg in hitrost obdelave podatkov. Projekt AugmentedCCAM – Advancing Infrastructure Readiness for Cooperative, Connected and Automated Mobility [3] je zato razvijal rešitve, ki razširjajo zaznavni doseg vozil ter izboljšujejo njihovo sposobnost varnega odločanja v prometu. Pri tem povezuje področja telekomunikacij, elektronike, digitalnih tehnologij in upravljanja prometnih sistemov.

Rešitve projekta temeljijo na sodelovanju vozil, infrastrukture in podpornih sistemov. V proces zbiranja, obdelave in izmenjave podatkov so vključene naprave ob cestni infrastrukturi, komunikacijski sistemi v vozilih, brezpilotni letalniki ter centralni podatkovni centri. Takšna integracija omogoča celovitejši pregled prometnih razmer in učinkovitejše delovanje povezanih ter avtomatiziranih vozil.

TESTNA OBMOČJA ZA PREVERJANJE REŠITEV CCAM

Študijski primeri projekta Augmented CCAM so bili preizkušeni na testnih območjih v Franciji, Latviji in Španiji, kjer so bile rešitve preverjene v realnih prometnih razmerah, nadzorovanih okoljih in simulacijah. Namen testiranja je bil oceniti pripravljenost fizične, digitalne in komunikacijske infrastrukture za podporo povezanim in avtomatiziranim vozilom [4].

V Franciji so testiranja potekala na treh lokacijah. Na odseku avtoceste A63 je bilo vzpostavljeno 25 kilometrov dolgo eksperimentalno območje za povezana vozila, opremljeno z obcestnimi komunikacijskimi enotami, naprednimi komunikacijskimi tehnologijami in sistemom za upravljanje prometa. Omogočalo je storitve, kot so opozarjanje na nevarnosti, cestna dela, upravljanje parkiranja in povezano patroliranje. Testno območje Satory pri Versaillesu je zagotavljalo zaprto in nadzorovano okolje z različnimi tipi cest ter naprednimi simulacijskimi zmogljivostmi (sliki 1 in 2) za preskušanje samovozečih vozil (slika 3).



Slika 1: Satory, Francija, računalniška simulacija študijskega primera.

Tretja lokacija je bil 32-kilometrski avtocestni odsek A10–A11 z odprtim prometom, ki je vključeval različne prometne in infrastrukturne scenarije, kot so cestninske postaje, vključitveni pasovi, avtobusni pasovi in območja za varno ustavljanje.



Slika 2: Satory, Francija, realistična simulacija dinamične vožnje.



Slika 3: Satory, Francija, uporabljeno samovozeče vozilo.

V Latviji sta bili vzpostavljeni dve testni območji. Prvo je obsegalo podeželske in primestne ceste v okolici mesta Ādaži z različnimi prometnimi obremenitvami in voznimi pogoji, po katerih sta peljali samovozeči vozili (sliki 4 in 5). Drugo območje je bilo umeščeno na dirkališče Biķernieki v Rigi, kjer je bilo v nadzorovanem okolju izvedeno prvo evropsko testiranje simulirane čezmejne povezljivosti 5G med latvijskim in estonskim mobilnim omrežjem.



Slika 4: Ādaži, Latvija, uporabljeno samovozeče vozilo (fotografijo posnel Janis Barbars).

Tudi v Španiji sta bili uporabljene dve lokaciji. V madridski mestni četrti Villaverde je bil vzpostavljen poligon v odprtem prometu, ki je povezanim vozilom omogočal vožnjo skozi različne prometne situacije, vključno s križišči, krožišči in prehodi za pešce. Območje je bilo opremljeno z vsemi potrebnimi elementi digitalne infrastrukture za preizkušanje naprednega upravljanja prometa. Drugo testno območje se je nahajalo v avtobusnem depolu Carabanchel, kjer so v delno nadzorovanem okolju preizkušali sodelovanje med povezanimi vozili, ranljivimi udeleženci v prometu in brezpilotnimi letalniki (sliki 6 in 7). V bližnjem urbanem okolju pa so bile izvedene tudi demonstracije storitev za prednostno obravnavo reševalnih vozil.

Skupaj so testna območja zagotavljala širok nabor prometnih scenarijev in infrastrukturnih pogojev, potrebnih za preverjanje učinkovitosti rešitev CCAM ter njihove prihodnje uvedbe v evropski prometni sistem.



Slika 5: Ādaži, Latvija, uporabljeni samovozeči vozili med študijskim primerom (fotografijo posnel Janis Barbars).



Slika 6: Madrid, Španija, simulacija vožnje enega izmed študijskih primerov (fotografijo posnela Ana Martinez Rosello).



Slika 7: Madrid, Španija, zaznavanje in obveščanje o pešcih med vožnjo povezanega avtobusa (fotografijo posnela Ana Martinez Rosello).

AUGMENTEDCCAM ŠTUDIJSKI PRIMERI

V okviru projekta je opredeljenih trinajst študijskih primerov oziroma PDI rešitev, ki predstavljajo ključne scenarije prihodnje uporabe povezanih, kooperativnih in avtomatiziranih prometnih sistemov. Namen teh primerov je preverjanje učinkovitosti fizične, digitalne in komunikacijske prometne infrastrukture, zbiranje podatkov o njenem delovanju ter ocena koristi za prometno varnost, pretočnost, trajnost in uporabniško izkušnjo [5].

Prvi študijski primer obravnava zgodnje opozarjanje na bližajoča se reševalna vozila. Povezano reševalno vozilo neprekinjeno sporoča svoj položaj in načrtovano pot drugim vozilom ter prometni infrastrukturi. Na podlagi teh informacij se lahko avtomatizirana in običajna vozila pravočasno odzovejo, prilagodijo svojo vožnjo in ustvarijo prosto pot. Posledica so hitrejši intervencijski časi, večja prometna varnost in manj motenj v prometnem toku.

Drugi primer je namenjen zaščiti ranljivih udeležencev v prometu, predvsem pešcev in kolesarjev, v okolici

avtomatiziranih avtobusov. Rešitev uporablja kamere, umetno inteligenco, digitalni dvojček območja in posebno mobilno aplikacijo. Sistem spremlja gibanje ranljivih udeležencev ter ocenjuje tveganja za konfliktna stanja. Opozorila so posredovana tako vozilom kot tudi udeležencem preko pametnih naprav z vizualnimi, zvočnimi ali vibracijskimi obvestili.

Tretji primer obravnava podobno problematiko, vendar brez uporabe mobilnih aplikacij. Zaščita ranljivih udeležencev temelji na komunikaciji med vozili in cestno infrastrukturo. Obcestne komunikacijske enote zbirajo informacije o položaju udeležencev in jih posredujejo avtomatiziranim vozilom, ki lahko pravočasno prilagodijo svoje manevre ter preprečijo nevarne situacije.

Četrty študijski primer se osredotoča na optimizacijo upravljanja prometa na podlagi podatkov, ki jih posredujejo povezana vozila. Vozila v realnem času pošiljajo informacije o svoji lokaciji, hitrosti, izvoru in cilju potovanja. Sistem za upravljanje prometa te podatke uporablja za izboljšano regulacijo prometnih tokov, preusmerjanje vozil na optimalne poti in prepoznavanje prometnih kritičnih točk. Dolgoročno takšna rešitev zmanjšuje zastoje, vplive na okolje in število prometnih nesreč.

Peti primer proučuje nove možnosti določanja položaja vozil in drugih objektov z uporabo omrežij 5G. Rešitev temelji na naprednih metodah lokalizacije, ki vključujejo določanje položaja na podlagi baznih postaj in podporo satelitskim navigacijskim sistemom. Namen je doseči visoko natančnost določanja lokacije ter izboljšati funkcionalnost in energetsko učinkovitost mobilnih storitev.

Šesti študijski primer obravnava manever minimalnega tveganja, ki ga izvede samovozeče vozilo ob zaznavi okvare ali izhoda iz območja, za katerega je usposobljeno za samodejno vožnjo. Sistem vozilu zagotavlja informacije o najbližjih varnih območjih za zaustavitev, kot so parkirišča, počivališča ali druga zatočišča. Vozilo nato samostojno načrtuje varno pot do izbranega mesta in zmanjša tveganje za prometne nesreče.

Sedmi primer je iz področja logistike. Rešitev omogoča optimizacijo dostavnih poti voznega parka z uporabo naprednih digitalnih orodij, rezervacije dostavnih mest in sprotne prilagajanja poti glede na razmere na terenu. Podprta je s specializirano platformo za upravljanje logističnih območij in parkirnih zmogljivosti. Cilj je zmanjšanje stroškov, boljša izraba vozil ter učinkovitejša dostava blaga.

Osmi študijski primer obravnava vključevanje vozil v prometni tok na avtocestnih priključkih. Napredni sistem zagotavlja informacije o prometnih razmerah, potencialnih nevarnostih in možnostih trkov. Samovozečim vozilom omogoča boljše napovedovanje situacij ter ustrezno prilagajanje hitrosti in voznih manevrov. S tem se izboljšuje varnost in tekočnost vključevanja v promet.

Deveti primer se nanaša na začasna dela na cesti. Delovna vozila in prikolice preko komunikacijskih sistemov sporočajo svojo lokacijo, dimenzije delovnega območja in predvideno trajanje del. Te informacije se vključijo v

digitalne zemljevide in posredujejo samovozečim vozilom. Vozila lahko nato izberejo ustrezno pot, prilagodijo način vožnje ali uporabijo obvoz. Povratne informacije vozil omogočajo dodatno preverjanje dejanskega stanja na terenu.

Deseti študijski primer je namenjen izboljšanju manevrov vključevanja samovozečih vozil. Sistem s pomočjo kamer in umetne inteligence zaznava objekte na avtocestnih priključkih in glavnih prometnih pasovih. Zbrane informacije se preko obcestnih enot in kooperativnih sporočil posredujejo vozilom, ki jih vključijo v svoje lokalne zemljevide. Tako lahko natančneje načrtujejo lastno vključevanje ali pomagajo drugim vozilom pri varnem vključevanju.

Enajsti primer ponovno obravnava približevanje reševalnih vozil, vendar s poudarkom na upravljanju celotnega prometnega sistema med nujnimi intervencijami. Cilj je zagotoviti prednostno obravnavo reševalnih vozil in optimizirati njihov čas prihoda na kraj dogodka, ob hkratnem obveščanju vseh drugih povezanih vozil. Po zaključku intervencije se prometni sistem vrne v običajen način delovanja.

Dvanajsti študijski primer uvaja uporabo brezпилotnih letalnikov za zaščito ranljivih udeležencev na zaprtih območjih, kot so avtobusni depoji. Brezпилotniki s kamerami spremljajo gibanje pešcev in drugih udeležencev ter informacije posredujejo avtomatiziranim vozilom. Dodatno sistem uporablja umetno inteligenco za ocenjevanje tveganja trkov in podporo pri načrtovanju varnih poti vozil.

Trinajsti primer združuje upravljanje območij del na cesti in zaščito cestnih delavcev. Samovozeča vozila preko sistema kooperativnih inteligentnih transportnih sistemov prejema podatke za posodobitev visoko ločljivih zemljevidov ter prilagajanje vožnje v območju del. Hkrati sistem opozarja delavce na približevanje vozil in obvešča voznike o nevarnih situacijah ter potrebi po zmanjšanju hitrosti. Tako se povečuje varnost tako delavcev kot vseh drugih udeležencev prometa.

Skupni imenovalec vseh predstavljenih študijskih primerov je uporaba naprednih komunikacijskih tehnologij, digitalnih zemljevidov, umetne inteligence, digitalnih dvojčkov, senzorjev in mobilnih omrežij nove generacije. Rešitve prispevajo k varnejšemu, učinkovitejšemu in trajnostnemu prometu, izboljšujejo sodelovanje med vozili in infrastrukturo ter predstavljajo pomemben korak k širši uvedbi povezanih in avtomatiziranih prometnih sistemov v prihodnosti.

V nadaljevanju sta podani dve tabeli. Prva tabela podaja primerjavo vseh trinajstih primerov uporabe s povzetimi glavnimi funkcionalnimi in podatkovnimi zahtevami, ter ključnimi tehnologijami, potrebnimi za izvedbo podporne PDI storitve oziroma študijskega primera. Druga tabela prikazuje tehnologije kot skupne gradnike fizične in digitalne infrastrukture ter prikazuje, v katerih študijskih primerih se posamezna tehnologija uporablja. Nekatere manj znane tehnologije v tabeli 1 so plod lastnega razvoja partnerjev projekta.

Tabela 1: Študijski primeri in njihove ključne funkcionalne in podatkovne zahteve ter tehnologije [5].

Študijski primer	Funkcionalne in podatkovne zahteve	Ključne uporabljene tehnologije
UC1 Blizajoče se reševalno vozilo	Posodabljanje globalnega visokoločiljivega (HD) zemljevida v realnem času; komunikacija med CAV, EV, RSU in TMC; deljenje lokacije in poti intervencijskega vozila; opozarjanje in koordinacija poti.	V2X dolgega dosega, DSRC, RSU z AI-kamerami, Sistem za upravljanje prometa (TMS), dinamični HD zemljevid, digitalni dvojček/senca.
UC2 Zaščita ranljivih udeležencev v prometu - z aplikacijo	AI-kamere zaznavajo in klasificirajo VRU; geografsko omejevanje nevarnih območij; sledenje VRU; opozorila vozilom; ETSI V2X komunikacija; napoved gibanja VRU.	AI-kamere, aplikacija VRU, VRU Manager, AURORA, MISTRAL, digitalni dvojček, Collision Risk Estimator, Connected Vehicle Manager, RSU, HD zemljevidi.
UC3 Zaščita ranljivih udeležencev v prometu - brez aplikacije	RSU z AI zazna VRU, klasificira tveganje in pošilja podatke vozilom ter v HD zemljevid.	AI-podprti RSU, dinamični HD zemljevid, komunikacije kratkega in dolgega dosega.
UC4 Optimizacija upravljanja prometa	Spremljanje vozil, izračun potovalnih časov, identifikacija črnih točk, priporočanje poti.	Connected Vehicle Manager, MISTRAL TMS, digitalni dvojček, AURORA, krmilniki semaforjev.
UC5 Lokalizacija različnih objektov in povezanih vozil	Zagotavljanje nizkozakasnitvenih lokacijskih podatkov preko omrežja 5G.	5G SA omrežje (Core + RAN + ENL), 5G modemi (3GPP Rel.16).
UC6 Manever minimalnega tveganja	Zaznavanje prostih varnih območij za ustavljanje; posredovanje podatkov preko V2X; podpora varnemu ustavljanju.	Cestni LiDARji, TMS, platforma I2V, RSU, oblačne storitve, POIM-PA/MAPEM/SPATEM sporočila, ADS vozilo z OBU.
UC7 Optimizirano logistično poslovanje	Optimizacija poti, rezervacija dostavnih mest, spremljanje zasedenosti, logistično planiranje, digitalni model.	Platforma za upravljanje logistike/flote, GNSS.
UC8 Vključevanje vozil v prometni tok	Zaznavanje vozil na vključevalnih pasovih, distribucija podatkov preko V2X, podpora vključevanju in sodelovalnim manevrom.	LiDAR na infrastrukturi, TMS, I2V platforma, RSU, oblak, CPM/DENM sporočila, ADS L3/L4 z OBU.
UC9 Območje začasnih del na cesti	Registracija cestnih del, posodobitev HD zemljevida, obveščanje vozil o deloviščih in omejitvah.	V2X dolgega dosega, prikolica za cestna dela (RWT), RSU z GNSS in AI-kamerami, TMS, dinamični HD zemljevidi.
UC10 Manever vključevanja samovoznega vozila	CCTV in AI zaznava objektov; ustvarjanje CPM; sprotno posodabljanje HD zemljevidov in podpora vključevanju.	C-ITS RSU, HD zemljevidi, TMS, C-ITS platforma, CCTV + AI analiza, CAM/CPM/DENM, zunanja podatkovna baza.
UC11 Približevanje reševalnega vozila	Kooperativni manevri za dajanje prednosti EV; optimizacija poti; prednost pri semaforjih.	Emergency Vehicle Manager, MISTRAL, digitalni dvojček, AURORA, krmilniki semaforjev, Connected Vehicle Manager.
UC12 Zaščita ranljivih udeležencev v prometu - z uporabo letalnikov	Spremljanje VRU z dronom, AI klasifikacija, V2X obveščanje in ocenjevanje tveganja trkov.	UAV z RTK-GNSS in kamero, RSU, bazna postaja, AI algoritmi zaznavanja, AI ocena tveganja, GNSS/RTK, V2X.
UC13 Obvestila o delih in delavcih na cesti	Posodobitve HD zemljevida, opozarjanje delavcev in vozil, upravljanje delovišč preko V2I/V2V komunikacij.	C-ITS RSU, C-ITS OBU, HD zemljevidi, TMS, C-ITS platforma, podatkovni strežnik, DENM in MAPEM.

Tabela 2: Tehnologije in študijski primeri, kjer se posamezna tehnologija uporablja.

LiDAR na infrastrukturi	UC6, UC8
Obladne storitve in platforme	UC4, UC6, UC8, UC10, UC11

Tehnologija	Študijski primeri, kjer je bila tehnologija uporabljena
Visokoločiljivostni zemljevid (HD map)	UC1, UC3, UC5, UC6, UC9, UC10, UC13
Digitalni dvojček (Digital Twin)	UC1, UC2, UC4, UC11
Obcestna postaja (RSU Road Side Unit)	UC1, UC2, UC3, UC6, UC8, UC9, UC10, UC12, UC13
AI kamere	UC1, UC2, UC3, UC9, UC10, UC12
Sistem za upravljanje prometa (TMS)	UC1, UC4, UC6, UC8, UC9, UC10, UC11, UC13
V2X komunikacije	Vsi, razen UC7
GNSS / pozicioniranje	UC5, UC7, UC9, UC12

Iz primerjave je razvidno, da so V2X komunikacije, RSU enote, HD/digitalni zemljevidi in sistemi za upravljanje prometa (TMS) najpogostejše uporabljeni gradniki in predstavljajo jedro digitalne infrastrukture projekta. Po drugi strani pa so nekatere tehnologije specifične za posamezne storitve, na primer UAV (droni – brezpilotni letalniki) v UC12, logistična platforma v UC7 ter LiDAR infrastruktura v UC6 in UC8.

FUNKCIONALNA VARNOST CESTNE INFRASTRUKTURE

Za vrednotenje podpornih storitev PDI za CCAM je bil v projektu razvit celovit okvir za sistematično oceno presojo infrastrukturnih naložb in tehnoloških inovacij na prometni sistem. Ta temelji na pilotnih preskusih v realnem prometnem okolju, prometnih simulacijah, digitalnem modeliranju ter analizah pripravljenosti cestne infrastrukture na kooperativno, povezano in avtomatizirano mobilnost.

Presoja zajema več področij: prometno varnost, prometno učinkovitost, funkcionalno varnost infrastrukture, vplive na okolje [6], zanesljivost storitev, kibernetsko varnost in zaupanje uporabnikov, vedenje voznikov ter družbeno-ekonomske stroške in koristi. S tem je mogoča ocena širših vplivov na družbo in prometne sisteme.

Posebno področje ocene učinkov predstavlja funkcionalna varnost infrastrukture. Ta temelji na dveh ključnih kazalnikih: pripravljenosti infrastrukture za CCAM in stopnji prevzema nadzora nad samovozečim vozilom (Disengagement Rate).

Prvi kazalnik ocenjuje stopnjo tehnološke zrelosti infrastrukture. V projektu je bila razvita harmonizirana klasifikacijska shema podpore PDI, ki opredeljuje pet ravni infrastrukturne podpore avtomatizirani vožnji, od osnovne infrastrukture za zaznavanje in načrtovanje, do napredne, usklajeno delujoče infrastrukture za podporo mešanim voznim parkom (ki vključuje običajna, neavtomatizirana vozila, preko kooperativnih vozil do samovozečih vozil različnih SAE stopenj). Takšna klasifikacija omogoča prepoznavanje infrastrukturnih vrzeli, določanje razvojnih prioritet in podporo interoperabilnosti med evropskimi prometnimi sistemi.

Za praktično uporabo klasifikacijske sheme je bilo razvito spletno orodje *Infrastructure Readiness for CCAM Assessment Tool* (slika 8). Z njim lahko upravljavci cest kartirajo cestne odseke, določijo njihove infrastrukturne značilnosti, ocenijo pripravljenost posameznih elementov, primerjajo odseke z različno stopnjo infrastrukturne podpore ter izračunajo oceno pripravljenosti. Orodje na koncu poda odstotno oceno zrelosti infrastrukture za vseh pet ravni infrastrukturne podpore avtomatizirani vožnji (slika 9). Primerjava med obstoječim stanjem in stanjem po načrtovanih izboljšavah jasno pokaže koristi vlaganj v PDI.

Drugi kazalnik, stopnja prevzema nadzora, meri zanesljivost delovanja avtomatiziranih sistemov. Prevzem nadzora nastopi, ko napredni sistemi za pomoč vozniku (ADAS) zaradi zahtevnih razmer predajo upravljanje vozniku ali ko voznik sam presodi, da je potreben poseg. Kazalnik se izračuna kot razmerje med številom primerov prevzema nadzora in skupnim številom izvedenih testov posamezne storitve PDI.

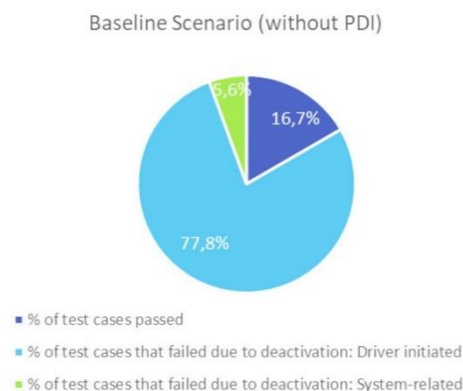
Rezultati projekta kažejo pomemben prispevek infrastrukturne podpore k varnejšemu in zanesljivejšemu delovanju avtomatiziranih vozil. V enem izmed primerov se je delež uspešno opravljenih testov povečal s 16,7 % v osnovnem scenariju na 90,2 % v scenariju z aktivirano podporno storitvijo PDI (sliki 10 in 11). To potrjuje, da ustrezno razvita infrastruktura bistveno izboljša delovanje

sistemov CCAM, zmanjša potrebo po prevzemu nadzora in poveča varnost ter zanesljivost avtomatizirane mobilnosti.

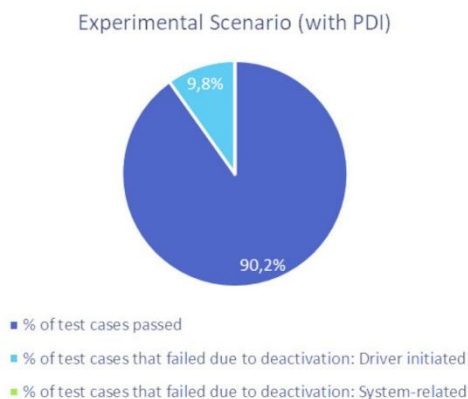
Slika 8: Posnetek zaslona dela spletnega orodja *Infrastructure Readiness for CCAM Assessment Tool* [7].



Slika 9: Primer končne ocene zrelosti infrastrukture [7].



Slika 10: Primer izračunane stopnje prevzema nadzora nad vozilom po osnovnem scenariju [7].



Slika 11: Primer izračunane stopnje prevzema nadzora nad vozilom po scenariju z aktivirano podporno storitvijo PDI [7].

ZAKLJUČKI

Projekt AugmentedCCAM je pokazal, da lahko upravljalci cest in oblikovalci prometnih politik z nadgradnjo fizične, digitalne in komunikacijske infrastrukture pomembno pospešijo uvajanje sistemov CCAM. Pri tem sklop infrastrukture, poimenovan PDI (Physical, Digital and Communication Infrastructure), predstavlja ključno podporo za prihodnji razvoj avtomatizirane mobilnosti.

Pomemben rezultat projekta so tudi preizkusi na realnih in zaprtih cestnih odsekih ter v simuliranih okoljih. Na podlagi teh testiranj so bila razvita ogrodja, metodologije in orodja, ki omogočajo prilagajanje prometne infrastrukture potrebam povezanih in avtomatiziranih vozil ter prispevajo k njihovi varni in učinkoviti vključitvi v prometne sisteme prihodnosti.

Nazadnje je bila v projektu razvita še celovita metodologija presoje različnih vplivov podpornih PDI rešitev na samo kooperativno, povezano in avtomatizirano mobilnost, ki je pokazala, da imajo le-te širok pozitiven učinek.

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SECURITY ARCHITECTURE OF THE EUROPEAN C-ITS TRUST FRAMEWORK

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Abstract

The deployment of Cooperative Intelligent Transport Systems (C-ITS) relies on open wireless communication among untrusted entities, raising critical security and privacy challenges that cannot be addressed by conventional information security models alone. This paper presents a systematic analysis of the security architecture underlying the European C-ITS trust framework. The study examines the hierarchical governance model comprising the Certificate Policy Authority (CPA), the European Certificate Trust List (ECTL), and the Central Point of Contact (CPOC). It further investigates the dual-certificate PKI mechanism separating Enrolment Credentials (EC) from pseudonymous Authorization Tickets (AT), alongside the compliance levels L0–L2 that define progressive policy enforcement from testing to full production deployment. The analysis also evaluates the cryptographic protection of operational messages, specifically the use of SHA-256 hashing and ECDSA signatures over NIST P-256 or BrainpoolP256r1 curves, as well as the bandwidth optimization achieved through HashedId8 certificate references.

Key findings indicate that the European framework enables interoperable and privacy-preserving V2X authentication while maintaining real-time performance constraints. The paper additionally outlines selected deployment challenges related to the coexistence of ITS-G5 and C-V2X communication technologies and their implications for future interoperable C-ITS deployments.

Keywords

C-ITS, V2X, security architecture, CPA, CPOC, PKI, digital certificates, trust management, ECTL, compliance levels L0-L2, ECDSA, pseudonymity, HashedId8

INTRODUCTION

The development of Cooperative Intelligent Transport Systems (C-ITS) represents an important step in the digital transformation of road transport and the deployment of cooperative mobility services based on direct information exchange among vehicles, roadside infrastructure, and traffic management centres. Such systems enable earlier detection of hazardous situations, more efficient traffic management, and support for advanced driver assistance systems as well as future levels of automated driving. European transport strategies [1-3] emphasize the reduction of traffic accidents, improved traffic efficiency, and mitigation of the environmental impact of transport, while interoperable C-ITS services play an important role within the broader vision of connected and digital mobility.

A distinctive characteristic of the C-ITS environment is that vehicles are no longer dependent solely on onboard sensors and local perception of the environment, but increasingly also on information received from other vehicles and the infrastructure. Vehicles may receive

warnings about hazards behind blind curves, sudden traffic congestion, emergency vehicles, slippery roads, or other traffic events before such situations are detected by drivers or onboard vehicle systems. Since such information may directly influence driver behaviour or vehicle operation, trust in received data becomes one of the key challenges of C-ITS systems.

Communication in C-ITS environments takes place among mutually unknown participants and over open wireless communication media, making such systems exposed to various security risks and malicious activities. Commonly discussed threats [4, 5] include dissemination of bogus traffic warnings, message tampering and forgery, spoofing or impersonation of vehicles and infrastructure, unauthorized access to services, and denial-of-service attacks. Protection of user privacy also represents a major challenge, since insufficiently protected systems may enable vehicle tracking, analysis of mobility patterns, or correlation of communication identities with actual users.

These threats span multiple complementary security domains that jointly define the security posture of C-ITS systems. As summarized in Table 1, the C-ITS security model extends beyond classical information security and cannot be adequately captured by a single-layer perspective. Instead, it represents a multi-layered security structure that spans from the physical safety of road users and operational reliability of traffic services to the protection of communication processes, cryptographic material, and long-term governance of trust relationships within the ecosystem.

Table 1: Security domains in C-ITS systems

Security domain	Primary objective
Traffic and functional safety	Prevention of accidents and protection of human life
Information security	Authenticity and integrity of exchanged messages
Commun. and network security	Availability and resilience of communication channels
Hardware and platform security	Protection of cryptographic material and trusted execution
Privacy protection	Prevention of vehicle tracking and identity correlation
Cybersecurity governance	Lifecycle management and system-level trust governance

This layered structure reflects the fact that security objectives in C-ITS are not isolated, but interdependent. Ensuring message authenticity alone is insufficient without maintaining system availability, just as cryptographic protection has limited value if operational continuity or privacy guarantees are compromised. Consequently, C-ITS security must be understood as an integrated framework in

which different domains jointly contribute to safe, reliable, and trustworthy system operation in a highly distributed and adversarial communication environment.

Security aspects of C-ITS systems differ in several ways from those of conventional information systems. Traditional information security models are commonly based on the principles of confidentiality, integrity, and availability (CIA triad), whereas cooperative transport systems primarily emphasize authenticity, integrity, and trustworthiness of exchanged messages due to the open nature of communication and the direct impact on road safety. Since communication often relies on periodic broadcast transmission of traffic-related information to surrounding participants, confidentiality is not always a primary objective. Instead, particular importance is placed on privacy protection [6], prevention of vehicle tracking, and assurance of the legitimacy of communicating entities.

Due to the large number of stakeholders, cross-border operation of services, and the need for interoperability among vehicle manufacturers, infrastructure operators, and service providers, the European approach [7] is based on a harmonized trust and digital identity management framework. This approach includes the use of Public Key Infrastructure (PKI), digital certificates, pseudonymous identities, and hierarchical trust models enabling verification of communication legitimacy without revealing the actual identity of users. Importance is assigned to interoperability of the security framework, technology neutrality, and harmonized trust management mechanisms among participating states and operators. Within the European environment, initiatives such as the C-Roads platform [8] and common European trust management mechanisms play an important role in the deployment of interoperable C-ITS services.

The purpose of this paper is to analyse key mechanisms ensuring information security and interoperable trust management within the EU C-ITS environment. It addresses how the EU trust framework enables secure and interoperable operation of heterogeneous C-ITS deployments, as well as the implementation constraints and development challenges observed in practice. The paper focuses on the architecture of the trust model, the use of PKI, digital certificate management, and interoperability mechanisms across stakeholders and communication technologies within the C-ITS ecosystem.

SCOPE AND RESEARCH METHODOLOGY

This paper is based on a combination of a review of scientific literature, technical publications, European standards, and architectural specifications in the field of C-ITS and related security mechanisms. The analysis incorporates peer-reviewed research addressing C-ITS security, privacy protection, trust management, and V2X communication, together with key ETSI documents, the architecture of the European trust model, and specifications related to PKI, digital certificate management, and C-ITS interoperability.

A significant part of the methodological approach is the examination of the European C-ITS trust framework and its associated governance, credential-management, and cryptographic protection mechanisms. The study analyzes the relationships among trust-management entities, certificate lifecycle processes, compliance structures, and security procedures used to establish authenticated and privacy-preserving V2X communication.

An additional methodological basis is participation in working groups and interoperability activities within the European C-Roads platform, where technical and operational challenges related to cross-border C-ITS interoperability were addressed. These activities provided practical insights into trust-management processes, deployment constraints, and interoperability requirements within the EU C-ITS ecosystem.

The empirical part is based on the observation of communication data and diagnostic records from C-ITS environments, including message exchanges between vehicles and roadside infrastructure. The analysis also includes inspection of network traffic, providing insight into message structures, certificate usage, digital signatures, and authentication mechanisms in real-world conditions.

The paper further applies a comparative analytical approach to examine ITS-G5 and C-V2X communication technologies with respect to trust management, certificate lifecycle procedures, interoperability considerations, and the technology-neutral security principles of the European C-ITS framework.

The paper is designed as an analytical study of trust management, cryptographic protection, and interoperability mechanisms in the European C-ITS environment, combining scientific literature review, standards analysis, and practical deployment experience from operational European C-ITS activities.

THE EU C-ITS TRUST AND PKI FRAMEWORK

The EU C-ITS trust framework combines centralized governance with a Public Key Infrastructure (PKI) to enable secure and interoperable vehicle-to-everything (V2X) communication across Europe. The architecture is structured into three complementary layers covering trust governance, certificate-based identity management, and system deployment with defined compliance levels. Together, these layers describe how trust is established, managed, and enforced across distributed stakeholders within the C-ITS ecosystem.

Governance and trust management structure

The EU C-ITS trust framework is governed through a hierarchical policy and operational structure centered around the Certificate Policy Authority (CPA). The CPA defines the Certificate Policy (CP) and Security Policy (SP), which specify the regulatory, organizational, and technical requirements for participation in the system [11, 12].

Operational trust management is delegated to the Trust List Manager (TLM) and the Central Point of Contact

(CPOC), which coordinate the integration of national Root Certification Authorities into the European Certificate Trust List (ECTL) [10]. The ECTL serves as the unified trust anchor enabling cross-border validation of certificates across all participating domains.

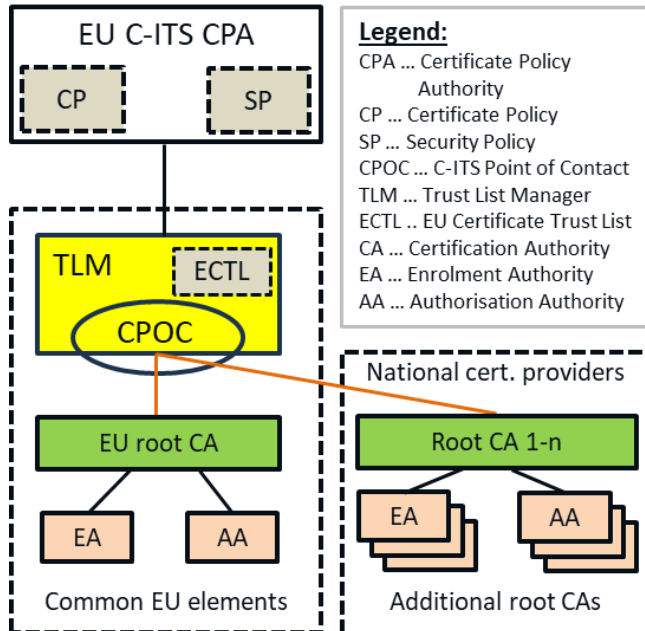


Figure 1: High level view of the EU CCMS trust model [10]

The governance hierarchy is illustrated in Figure 1, showing the trust flow from CPA through TLM and CPOC to Root Certification Authorities and further down to Enrolment Authorities (EA) and Authorisation Authorities (AA). This structure defines how policy-level trust decisions are translated into operational certificate issuance and validation.

PKI-based credential and trust model

The C-ITS trust infrastructure is implemented using a PKI-based model in which Root Certification Authorities (RCAs) represent the primary trust anchors of the system [13]. These authorities delegate operational responsibilities to EA and AA entities, separating long-term identity provisioning from short-term message authorization to enforce privacy by design. The EA manages long-term enrolment and issues Enrolment Credentials (EC) to authenticated stations, meaning it knows the true identity of the vehicle but has no visibility into its active communication.

Conversely, the AA issues short-term Authorization Tickets (AT) used for pseudonymous V2X communication [14]. Due to a cryptographic separation of duties, the AA is completely unaware of the vehicle's real identity, yet it is empowered to grant operational permissions to anonymous stations. To minimize communication overhead and latency during driving, ATs are requested from the infrastructure well in advance. Stations typically download a pool of multiple ATs simultaneously, which are then stored locally, periodically renewed, and dynamically rotated. This

structural isolation and proactive provisioning effectively enable message authentication while preventing the long-term tracking of participating vehicles or infrastructure nodes [13, 14].

Certificate lifecycle management includes issuance, renewal, and revocation. Revocation is enforced through Certificate Revocation Lists (CRLs), ensuring that compromised credentials are excluded from the trust domain [11]. A structured overview of the PKI credential model is provided in Table 2.

Table 2: PKI credential model in EU C-ITS

Element	Primary objective
Root CA certificate	Trust anchor for certificate chain validation
Enrolment Credential (EC)	Long-term identity binding for authentication
Authorization Ticket (AT)	Short-term pseudonymous credential for V2X signing
Certificate Revocation List (CRL)	Revocation enforcement mechanism
European Certificate Trust List (ECTL)	Cross-border trust registry element

System deployment and compliance levels

The EU C-ITS deployment model defines three compliance levels, L0, L1, and L2, which regulate the progressive introduction of C-ITS services under a unified trust framework [10, 11]. In this context, compliance refers to the degree of enforcement of security governance, audit requirements, cryptographic controls, and operational constraints defined by the Certificate Policy (CP), Security Policy (SP), and the CPOC protocol. It therefore represents a structured enforcement gradient ranging from relaxed policy validation to fully enforced certification regimes. The relationship between L0–L2 compliance levels and their deployment evolution is illustrated in Figure 2 [10].

L0 represents a controlled testing environment used for functional validation without production certification requirements. At this level, systems operate outside the full scope of CP/SP enforcement and are primarily used for functional and interoperability testing in isolated environments.

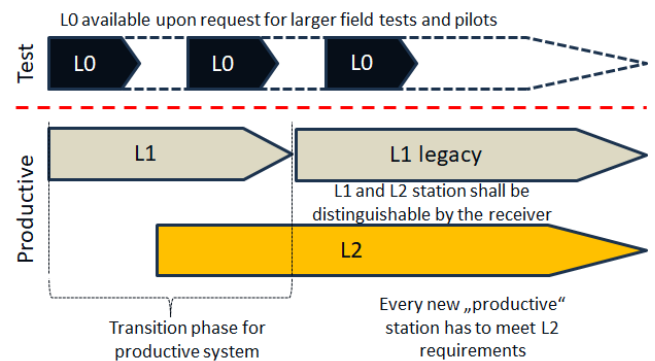


Figure 2: Overview and timeline of ECTL levels [10]

L1 represents a transitional deployment phase enabling limited real-world operation under a policy-relaxed compliance regime. In this phase, the CPOC protocol defines a set of controlled exceptions to full L2 requirements [10]. These exceptions include alternative security management approaches when ISO 27001 ISMS is not available, the use of internal or self-declared compliance audits instead of mandatory external certification, and transitional evaluation pathways for secure elements and C-ITS station validation.

Additional exceptions cover certification flexibility for hardware and software components, including the use of accredited or equivalent testing laboratories and phased compliance reporting for secure elements during the transition period. Empirical deployment experience confirms that L1 operates as a hybrid trust model combining PKI-based delegation with transitional governance and internal audit mechanisms [15].

L2 represents full production deployment and defines the highest compliance level within the CCMS framework. At this level, all CP and SP requirements are fully enforced without exceptions. This includes mandatory external audits, standardized ISMS scope enforcement, and strict compliance with certified security requirements across all system components.

Cryptographic operations are fully controlled through certified Hardware Security Modules (HSMs), ensuring secure generation, storage, and lifecycle management of cryptographic key material [11, 12]. Unlike L1, no relaxation of requirements is permitted, and all PKI operations and validation processes must conform to fully standardized certification procedures.

The fundamental distinction between L1 and L2 lies in the enforcement regime rather than the presence of security controls. L1 is defined by an exception-based compliance model governed by the CPOC protocol [10] and validated through early deployment experience [15], whereas L2 enforces a fully standardized and externally audited security baseline without deviations.

Looking beyond the currently established architecture, the framework is designed to scale dynamically through the future introduction of higher levels, denoted as L_n (where $n > 2$). Any additional level will inherit the baseline trust of the preceding environment while introducing stricter operational and technical mandates, which are expected to be necessary for cooperative automated driving systems. While L2 remains the highest defined standard today, the CPA is already evaluating subsequent iterations to address emerging cryptographic threats posed by quantum computing [13]. Although not officially designated as Level 3, these future extensions are expected to include the integration of Post-Quantum Cryptography (PQC) [16], aimed at ensuring long-term resilience of the C-ITS trust framework against adversaries capable of breaking classical public-key cryptographic algorithms such as RSA and elliptic curve cryptography.

CRYPTOGRAPHY AND PUBLIC KEY INFRASTRUCTURE

This section focuses on the cryptographic mechanisms that protect exchanged information during operational communication. The security architecture relies on asymmetric cryptography and digital certificates to ensure that received messages originate from legitimate participants and have not been modified during transmission.

Cryptographic protection of C-ITS messages

C-ITS communication is based on the exchange of standardized information messages among vehicles, roadside infrastructure, traffic management centres, and other participating entities. Depending on their purpose, messages may be transmitted periodically or triggered by specific traffic events. A representative overview of common C-ITS message types and their transmission characteristics is provided in Table 3 [17].

Table 3: C-ITS message transmission model [17]

Message type	Message sender	Transmission model
CAM	V-ITS-S / R-ITS-S	Dynamic/Fixed period.
DENM	V-ITS-S / R-ITS-S	Event-trig. -> Periodic
SPATEM	R-ITS-S	Fixed periodic
MAPEM	R-ITS-S	Fixed periodic
IVIM	R-ITS-S	Event-trig. -> Periodic

CAM (Cooperative Awareness Message) is transmitted periodically by both vehicles (V-ITS-S) and roadside infrastructure (R-ITS-S) to share position, speed, and dynamic state information. Vehicles adjust transmission rates according to driving conditions, typically between 1 and 10 Hz, while roadside units usually transmit at fixed intervals [18]. DENM (Decentralized Environmental Notification Message) is generated when a specific event occurs, such as a detected hazard, accident, roadworks, or adverse weather conditions, and is subsequently repeated for a limited validity period. SPATEM and MAPEM provide traffic signal phase information and intersection topology data, while IVIM (In-vehicle Information Messages) distributes infrastructure-based information such as speed limits or temporary traffic restrictions [17].

In dense traffic environments, hundreds of stations may simultaneously exchange operational information, resulting in a very large number of transmitted messages. Regardless of their application purpose, all safety-relevant messages are protected using the same cryptographic framework.

Unlike conventional IT systems, confidentiality is generally not the primary objective for operational V2X communication. Safety-related information must remain immediately accessible to all nearby participants and is therefore typically transmitted as unencrypted payload data. Security is instead achieved through cryptographic mechanisms that provide message integrity, sender authentication, and trust verification [14, 19].

Cryptographic processing, certificates and trust validation

All protected C-ITS messages follow the same security processing model. Before transmission, application data is transformed into a standardized protocol structure, cryptographically protected, encapsulated into a secured message, and transmitted over the ITS-G5 communication stack. The complete transmission process is illustrated in Figure 3.

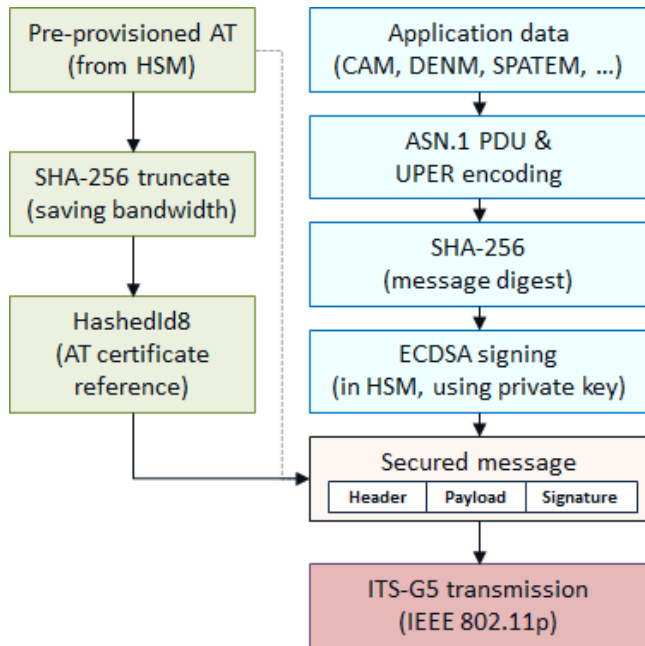


Figure 3: Transmission process of C-ITS messages

The process begins with application data generated by a transmitting station. Depending on the message type, this information may contain vehicle dynamics, hazard notifications, signal timing information, road topology descriptions, or other traffic-related data. Before cryptographic protection can be applied, the information is organized into an ASN.1 Protocol Data Unit (PDU) defined by the corresponding ETSI message specification and subsequently encoded using Unaligned Packed Encoding Rules (UPER), producing a compact binary representation optimized for low-latency wireless transmission [20].

The encoded payload enters the operational signing pipeline, a step that directly utilizes a pre-provisioned AT certificate. To initiate this process, the station fetches the currently active AT from its local storage. This certificate, previously issued by the AA, already embeds the station's cryptographic public key along with its specific operational privileges, defined via ITS Application Identifiers (ITS-AID) and Service Specific Permissions (SSP). The station then uses the corresponding private key, which is securely generated and retained within the HSM, to compute the ECDSA signature over the data. The generated signature and the corresponding AT information are subsequently incorporated into the Secured message structure [13, 14].

The UPER-encoded payload is processed using the SHA-256 cryptographic hash function, which generates a fixed-length digest uniquely representing the protected content

[11, 12]. Any modification of the payload would result in a different digest value and consequently invalidate the signature verification process. ETSI security profiles primarily use SHA-256 for operational message protection, while stronger hash algorithms such as SHA-384 are reserved for selected trust-management artefacts requiring extended cryptographic protection, including Root CA certificates and trust infrastructure components [11, 12].

The generated digest is subsequently signed using the Elliptic Curve Digital Signature Algorithm (ECDSA) and the private key associated with the Authorization Ticket [19]. ETSI security specifications support both NIST P-256 and BrainpoolP256r1 elliptic curves. In practical deployments, NIST P-256 is frequently preferred, as illustrated in Figure 4 from Slovenian testbed, due to broader hardware support and optimized implementation within automotive security modules, resulting in lower computational overhead and faster cryptographic operations [19, 21].

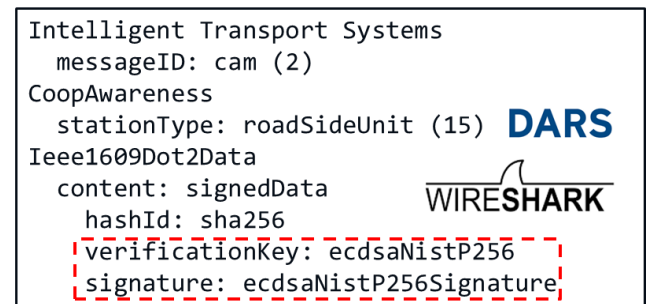


Figure 4: Wireshark excerpt of RSU-transmitted CAM

The transmitting station also includes a compact reference to the AT used for signing. Rather than transmitting the complete AT certificate with every message, ETSI security protocols normally include a HashedId8 value derived from the certificate [19]. The HashedId8 identifier consists of the 8 least significant bytes of the certificate hash and enables efficient certificate retrieval by the receiving station while minimizing communication overhead. In specific scenarios, such as periodic certificate dissemination, the complete AT certificate may be attached instead.

The certificate reference, protected payload, and ECDSA signature are then assembled into an ETSI Secured message structure and transmitted via the ITS-G5 communication stack [19].

Upon reception, illustrated in Figure 5, the receiving station extracts the HashedId8 value from the Security header and uses it to locate the corresponding AT within its local certificate cache [19]. The retrieved sender's AT contains the public key required for signature verification. At the same time, the receiver decodes the received payload using the corresponding ASN.1 specification and UPER. The decoded or raw payload is then processed through the same SHA-256 algorithm to recompute the message digest from the received content.

The recomputed digest, the received ECDSA signature, and the public key contained in the retrieved AT are then used during the verification procedure. Successful verification confirms that the message originated from the holder of the corresponding private key and that the

protected payload has not been modified during transmission.

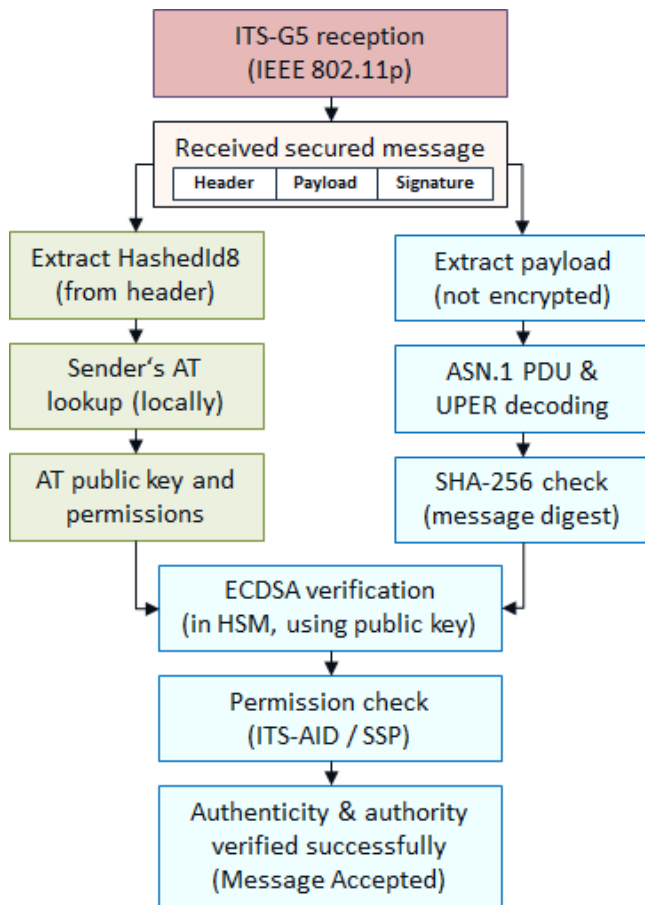


Figure 5: Reception process of C-ITS messages

Immediately following this mathematical validation, the receiver parses the SSP and ITS-AID embedded within the AT. This step evaluates whether the anonymous transmitter possesses the legitimate authority to issue that specific profile of V2X data, thereby validating the entire chain of trust. Any failure during these validation steps, whether due to a certificate cache miss, cryptographic mismatch during ECDSA verification, or insufficient SSP rights, causes the receiving station to immediately drop the message and log a security exception.

The workflow therefore combines message integrity protection, sender authentication, certificate-based trust establishment, and pseudonymous operation within a single verification process. Although ATs are periodically obtained from the PKI backend infrastructure via dedicated trust-management procedures via EA and AA, operational ITS-G5 communication relies exclusively on the AT currently selected by the transmitting station for message signing [13, 14].

ETSI packet structure and transmission efficiency

The cryptographic elements illustrated in Figures 3 and 5 are transported within the ETSI SecuredMessage structure defined by ETSI TS 103 097 [19]. The structure separates

certificate-related information, protected application data, and cryptographic signatures into dedicated fields optimized for low-latency wireless communication. A simplified representation of the secured packet structure is shown in Figure 6.

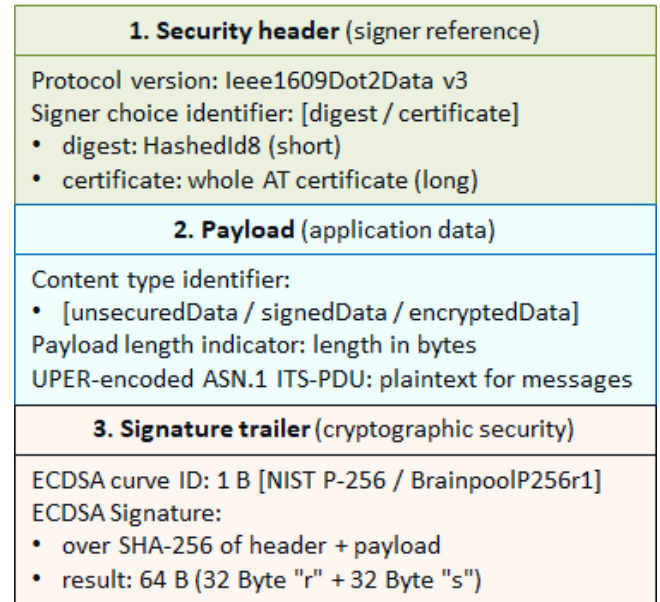


Figure 6: Structure of ETSI “SecuredMessage” packet

The Security header contains information required to identify the certificate used during message signing. In most transmissions, this information is represented by the HashedId8 value derived from the sender's AT. The Payload contains the ASN.1 message encoded using UPER, while the Security trailer stores the ECDSA signature generated by the sender's private key [19].

This organization enables efficient receiver-side processing. As soon as the Security header is received, the station can begin certificate lookup using the HashedId8 reference while reception of the remaining packet continues. The corresponding sender's AT can therefore be retrieved from the local certificate cache before the payload verification process is completed.

To avoid excessive communication overhead, complete AT certificates are not transmitted with every message. Instead, stations normally include only the HashedId8 reference, while complete AT certificates are transmitted periodically [19]. This mechanism allows newly arrived stations to obtain previously unknown certificates and compensates for packet loss that may occur in dynamic wireless communication environments. As a result, certificate caches remain synchronized even when communication conditions are imperfect.

The practical effect of this optimization can be observed in real communication captures. Figure 7 presents a Wireshark capture containing a sequence of CAM messages transmitted by a roadside unit. Most messages contain only the HashedId8 certificate reference and therefore occupy 237 bytes (short), while periodic messages carrying the complete AT certificate reach 410 bytes (long).

No.	Time	Source	Destination	Protocol	Length	Info
6018	1381.937824	0.5...	Broadcast	CAM	237	CAM
6019	1382.037144	0.5...	Broadcast	CAM LONG	410	CAM
6020	1382.145084	0.5...	Broadcast	CAM (1/10 t)	237	CAM
6021	1382.246300	0.5...	Broadcast	CAM	237	CAM
6022	1382.350827	0.5...	Broadcast	CAM	237	CAM
6023	1382.450546	0.5...	Broadcast	CAM	237	CAM
6024	1382.552570	0.5...	Broadcast	CAM SHORT	237	CAM
6025	1382.654712	0.5...	Broadcast	CAM (9/10 t)	237	CAM
6026	1382.757076	0.5...	Broadcast	CAM	237	CAM
6027	1382.860559	0.5...	Broadcast	CAM	237	CAM
6028	1382.962109	0.5...	Broadcast	CAM	237	CAM
6029	1383.056616	0.5...	Broadcast	CAM LONG	410	CAM

Figure 7: Wireshark capture of periodic CAM transmission

The Wireshark Length field represents the total size of the captured ITS-G5 frame. Comparing the observed packet sizes shows that inclusion of the complete AT increases the transmitted frame size by 173 bytes. Consequently, messages carrying only the HashedId8 reference reduce certificate-related communication overhead by approximately 42% compared to messages containing a complete AT certificate.

In the Wireshark security dissection, packets carrying only a certificate reference are typically indicated as Signer: digest, while packets transporting the complete certificate are indicated as Signer: certificate. The periodic appearance of certificate-bearing packets confirms the certificate dissemination mechanism defined by ETSI security specifications and described in the previous section [19].

By combining certificate caching, compact HashedId8 references, cryptographic hashing, digital signatures, and certificate-based trust validation, the ETSI security framework achieves scalable authentication while maintaining the low latency required for real-time cooperative transport services [14, 19].

DISCUSSION ON FUTURE-PROOF C-ITS TRUST AND HYBRID INTEROPERABILITY

The Slovenian C-ITS ecosystem currently relies primarily on ITS-G5 communication. Operational deployments were initiated within the C-ROADS platform and are already present on selected motorway sections managed by operator DARS [22], including parts of the Ljubljana ring. Meanwhile, additional ITS-G5 roadside infrastructure upgrades are planned within the urban road network managed by the Municipality of Ljubljana (MOL) under the X4ITS project [23]. Operational C-V2X deployments have not yet been introduced in Slovenia, although the technology is increasingly considered in future roadside infrastructure planning and procurement processes.

From a security perspective, however, the protected object remains the same in both ecosystems: the V2X message itself. Digital signatures, certificate chains, authorization validation, and trust establishment operate independently of the underlying radio technology. Consequently, the PKI trust model described in Sections 3 and 4 remains largely identical for both ITS-G5 and C-V2X deployments.

The transition from ITS-G5 towards C-V2X therefore does not fundamentally alter the trust architecture. Both

communication paradigms rely on PKI-based authentication, pseudonymous AT certificates, cryptographic hashing, ECDSA signatures, certificate revocation mechanisms, and common trust-anchor structures [24]. In both cases, security is applied at the message level rather than at the transport level, ensuring that authenticated messages can be validated regardless of the communication technology used for delivery.

Despite these similarities, practical differences emerge in the operational management of trust infrastructure. One of the most significant distinctions concerns certificate lifecycle management. ITS-G5 stations operating without a separate Internet connection cannot directly communicate with backend PKI services. Consequently, certificate renewal, trust-list updates, and certificate revocation information require an auxiliary IP-based connection, typically provided through wired infrastructure, external LTE modems, or maintenance procedures. Alternatively, for pilot deployments, a temporary workaround can be applied where AT and other security parameters are pre-loaded in an office environment with a significantly extended validity period. In contrast, C-V2X devices are generally connected to mobile networks through the Uu interface, enabling continuous connectivity to backend trust services and facilitating automated certificate provisioning, renewal, and revocation updates.

A comparison of selected ITS-G5 and C-V2X trust-management characteristics is presented in Table 4.

Table 4: Comparison of trust management characteristics in ITS-G5 and C-V2X

Aspect	ITS-G5	C-V2X
Trust model	PKI-based	PKI-based
Message security	ETSI TS 103 097	ETSI TS 103 097
Authentication method	EC and AT certificates	EC and AT certificates
Message signing	ECDSA	ECDSA
Certificate renewal	Requires external IP connectivity	Integrated via Uu connectivity
Revocation updates	Periodic sync.	Near real-time sync.
Direct communication	ITS-G5 radio link	PC5 sidelink
Infrastructure-assisted communication	External IP networks	Uu interface
MEC integration	Optional	Native ecosystem

The comparison demonstrates that the principal differences between ITS-G5 and C-V2X do not originate from the cryptographic trust model itself but rather from the communication infrastructure used to support trust-management operations. While message authentication, integrity verification, and authorization validation remain essentially identical, certificate distribution and trust-maintenance procedures become more tightly integrated with mobile-network infrastructure in C-V2X environments.

An additional distinction emerges when considering Multi-access Edge Computing (MEC) [25]. ITS-G5 was originally designed as a decentralized ad-hoc communication technology and does not inherently require edge-computing infrastructure. Although ITS-G5 deployments may utilize external edge platforms, such integration is not part of the core architecture. In contrast, modern C-V2X ecosystems increasingly incorporate MEC platforms directly within mobile operator networks. While cryptographic protection mechanisms remain unchanged, MEC enables localized processing of V2X information near the radio access network, reducing latency for advanced services such as cooperative perception, sensor sharing, dynamic traffic management, and cloud-assisted automated driving functions.

The coexistence of both communication paradigms has led to increasing interest in hybrid C-ITS deployments. Rather than replacing ITS-G5, current deployment strategies frequently combine both technologies. Safety-critical low-latency information may be exchanged directly through ITS-G5 or PC5 sidelink communication, while less time-sensitive services, trust-management functions, software updates, and cloud-assisted applications utilize mobile-network connectivity through the Uu interface. From the perspective of trust establishment, such hybrid architectures remain compatible because the same PKI framework, certificate hierarchy, and trust anchors can be used across multiple communication technologies.

This convergence of communication technologies suggests that future C-ITS deployments will likely be defined less by the underlying radio interface and more by their ability to maintain interoperable trust relationships across heterogeneous communication environments. The common EU PKI framework, including shared trust anchors, certificate policies, and ECTL distribution mechanisms, therefore represents a key enabler for long-term interoperability regardless of whether authenticated V2X messages are exchanged via ITS-G5, PC5 sidelink communication, or future hybrid architectures.

CONCLUSIONS

This paper examined the trust architecture and cryptographic protection mechanisms used within the European C-ITS ecosystem. The analysis focused on the PKI-based trust model and its role in establishing authenticated and trustworthy communication among participating transport-system entities.

The presented message-processing workflow demonstrated how cryptographic hashing, digital signatures, certificate validation, and authorization checks collectively provide message authenticity, integrity, and trust verification while supporting pseudonymous operation. Practical observations from ITS-G5 deployments further illustrated the efficiency benefits of certificate-reference mechanisms and their importance for scalable low-latency communication.

Although communication technologies are evolving towards C-V2X and hybrid architectures, the underlying

trust model remains largely unchanged. The results indicate that long-term interoperability depends primarily on maintaining a common PKI framework rather than on the selection of a specific radio-access technology.

Trust management therefore remains a fundamental enabling component of secure, interoperable, and future-proof cooperative transport systems.

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BIOGRAPHIE

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POTENTIAL AND EFFECTIVENESS OF DIAGONAL PEDESTRIAN CROSSINGS IN URBAN AREAS

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Abstract

This paper examines the potential of introducing diagonal crossings (pedestrian scramble) and an exclusive pedestrian phase as an alternative configuration at signalized intersections. Using a traffic microsimulation tool, the traffic impacts of such a layout were analyzed, primarily focusing on the effect of varying levels of pedestrian demand on overall traffic flow and delays. Special attention is given to building upon the findings of previous international studies by incorporating previously overlooked factors. Based on simulation results derived from both a hypothetical model and a real-world urban intersection, traffic volume thresholds were established at which the implementation of an exclusive phase is both justified and effective. The findings indicate that, provided the appropriate conditions are evaluated and met, such measures can significantly contribute to the design of safer and more pedestrian-friendly urban traffic environments.

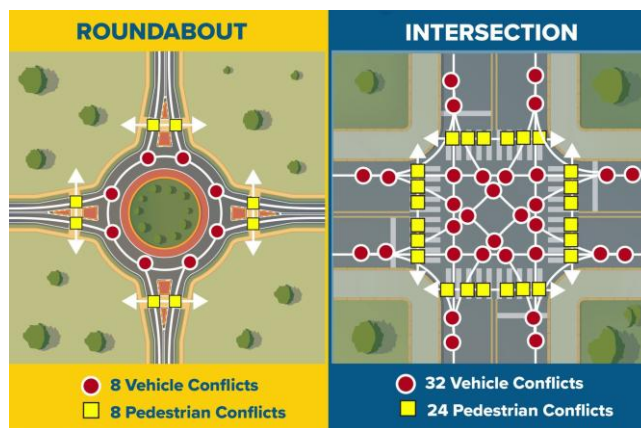
Keywords

intersections, delay, microsimulation, traffic safety, traffic flow

UVOD

Zaradi intenzivne urbanizacije in rasti prometa so prostorski ter transportni izzivi postali eno ključnih razvojnih vprašanj mest po vsem svetu. Z nenehnim povečevanjem urbanega prebivalstva in spodbujanjem trajnostne mobilnosti se v mestnih jedrih delež pešcev bistveno povečuje. Peš promet predstavlja enega najbolj trajnostnih in okolju prijaznih načinov prevoza, vendar pa njegova rastoča gostota ustvarja resne kapacitetne in varnostne konflikte z obstoječimi motoriziranimi tokovi. Tradicionalno prometno načrtovanje je semaforizirana križišča primarno prilagajalo čim večjemu pretoku vozil, zaradi česar so pešci pogo-sto potisnjeni v podrejen položaj s predolgimi čakalnimi dobami in nevarnimi konfliktnimi situacijami pri prečkanju cestišča.

V klasičnih semaforiziranih križiščih pešci prečkajo cesto sočasno z vozili, ki vozijo v isti smeri. To neizogibno vodi do konfliktnih točk, zlasti pri vozilih, ki v križišču zavijajo levo ali desno in prečijo prehod za pešce. Kot prikazuje slika 1, se v standardnem štirikrakem križišču med vozili in pešci pojavi natanko 24 konfliktnih točk. V krožnem križišču je teh konfliktov s pešci samo 8. Ti konflikti ne ogrožajo le prometne varnosti najbolj ranljivih udeležencev, temveč neposredno zmanjšujejo pretočnost cestišča. Vozila, ki zavijajo, morajo namreč pogosto ustavljati sredi križišča in čakati na prehod pešcev, kar povzroča veržne zastoje in kopičenje kolon na prometnih pasovih.



Slika 1: Shematski prikaz konfliktnih točk (vir: New York State Department of Transportation)

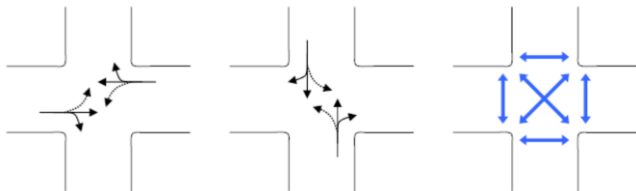
Za reševanje teh varnostnih in pretočnih izzivov so se v tujini uveljavili alternativni prometni režimi. Med najbolj učinkovitimi in prepoznavnimi je t.i. »križni prehod« s posebno fazo za pešce (ang. exclusive pedestrian phasing - PFP ali pedestrian scramble / Barnes Dance). Gre za prometno-tehnični ukrep, pri katerem se v semaforškem ciklu vsem vozilom na vseh krakih prižge rdeča luč, pešcem pa se omogoči povsem neovirano prečkanje križišča v vseh smereh, vključno z diagonalno. Ker v slovenskem prostoru tovrstna ureditev še ni bila implementirana, je cilj tega prispevka strokovno ovrednotiti njen potencial, določiti robne pogoje za smiselno uvedbo ter na realnem primeru v Ljubljani preveriti njeno izvedljivost. Glavna prednost je, da ne pride do niti enega konflikta z vozili.

TEORETIČNE OSNOVE IN PRIMERJAVA REŽIMOV

Konflikti med pešci in motornim prometom se v teoriji upravljanja prometa rešujejo z različnimi stopnjami časovnega ločevanja prometnih tokov. Med enostavnejše ukrepe sodi pred-faza za pešce (ang. Leading Pedestrian Interval – LPI), pri kateri pešci dobijo zeleno luč nekaj sekund pred vozili. Takšna ureditev izboljša njihovo vidnost in zmanjša verjetnost konfliktov z zavijajočimi vozili, vendar konfliktnih točk ne odpravlja v celoti. Najvišjo stopnjo varnosti predstavlja posebna faza za pešce (PFP), pri kateri imajo pešci zeleno luč v samostojni fazi semaforškega cikla, medtem ko imajo vsa vozila rdečo luč. S tem se v celoti odpravijo vsi konflikti med pešci in voznimi tokovi znotraj križišča.

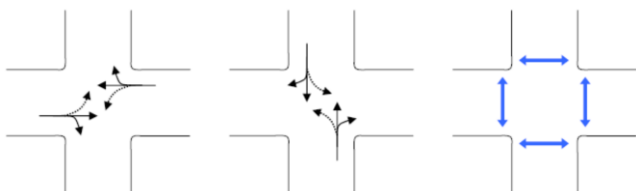
Glede na prostorske, geometrijske in prometne značilnosti križišč razlikujemo tri osnovne tipe ureditve PFP:

1. Tip A: Predstavlja absolutno ločitev in je najbolj učinkovit z vidika varnosti. Pešci lahko križišče prečkajo izključno v svoji namenski fazi (tako klasično kot diagonalno), v času zelenih luči za vozila pa je prehod strogo prepovedan. S tem se povsem preprečijo konfliktni točki med zavijajočimi vozili in pešci.



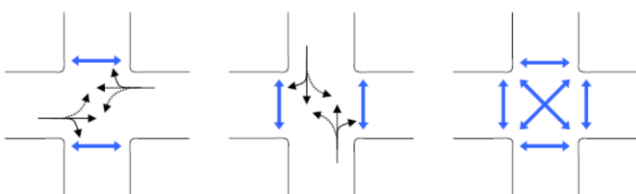
Slika 2: Prikaz posebne faze za pešce (PFP) TIP A

2. Tip B: Podoben tipu A, vendar zaradi specifične nepravilne geometrije križišča ali predolgh diagonalnih razdalj (nad 36 m) diagonalni prehodi niso označeni. Pešci prečkajo le v klasičnih smereh, vendar še vedno izključno v ločeni peščevi fazi.



Slika 3: Prikaz posebne faze za pešce (PFP) TIP B

3. Tip C: Predstavlja hibridno ureditev, kjer imajo pešci možnost prehajanja v svoji posebni fazi (tudi diagonalno), hkrati pa jim je prehod dovoljen tudi v fazi vozil v isti smeri. Ta tip se uporablja predvsem na lokacijah z izjemno velikim številom pešcev in majhnimi čakalnimi površinami na pločnikih, saj omogoča sprotno praznjenje površin, vendar pa ne odpravlja vseh konfliktnih točk z zavijajočimi vozili.



Slika 4: Prikaz posebne faze za pešce (PFP) TIP C

MEDNARODNE IZKUŠNJE IN PROSTORSKE OMEJITVE

Številna mesta po svetu že več desetletij uspešno uporabljajo križne prehode. V Torontu (npr. križišče Yonge St. in Dundas St.) in Calgaryju se je uvedba PFP izkazala za izjemno uspešno pri zmanjševanju ne-sreč s pešci, pri čemer so varnost nadgradili s semaforскими glavami z odštevalniki časa.



Slika 5: križišče Yonge St. in Dundas St. v Torontu

V Los Angelesu (Santa Monica) so opazili, da se ob uvedbi PFP tok vozil med svojo fazo premika bistveno bolj homogeno in z manj ustavljanji, saj jih ne ovirajo pešci.

Vendar pa so tuje študije jasno opredelile geometrijsko mejo: dolžina diagonalnih prehodov ne sme presegati 30 do 36 metrov. Daljši prehodi namreč zahtevajo pre-dolge varovane in praznilne čase, kar podaljša celotni semaforški cikel in poslabša prepustnost celotnega križišča.

METODOLOGIJA MIKROSIMULACIJSKEGA MODELIRANJA

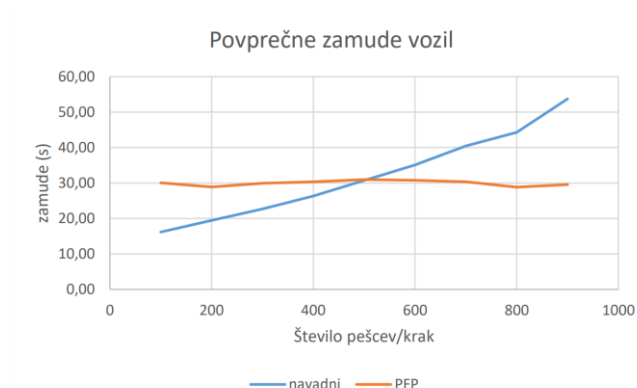
Za natančno določitev prometnih učinkov in smiselnosti uvedbe križnih prehodov je bil izdelan podroben mikrosimulacijski model v programskem orodju PTV Vissim. Za razliko od analitičnih metod mikrosimulacija simulira vsako posamezno vozilo in pešca kot samostojen objekt. Gibanje vozil temelji na psihofizičnem modelu sledenja vozil Wiedemann 74 (Wiedemann, 1974), medtem ko je bilo gibanje pešcev zmodelirano z naprednim modelom socialnih sil (Social Force Model), ki realistično simulira interakcije, izogiba-nje in prenatrpanost na čakalnih površinah pločnikov.

Splošna analiza je bila izvedena na generičnem pravokotnem štirikrakem križišču z ločenimi pasovi za leve zavijalce dolžine 80 m in širine pasov 3,0 m. Širina prehodov za pešce znaša 3,5 m. Obremenitev vozil je bila nastavljena konstantno na 300 vozil/krak/h (skupno 1200 vozil/h), kar zagotavlja, da začetno stanje deluje v stabilnem nivoju uslug (NU C ali boljše). Smerna razporeditev vozil je določena kot: 25 % levih zavijalcev, 40 % vožnje naravnost in 35 % desnih zavijalcev (skupaj kar 60 % zavijalcev, ki potencialno ogro-žajo pešce). Obremenitev pešcev je bila stopnjevana od 100 do 900 pešcev/krak/h (skupaj 400 do 3600 pešcev/h), pri čemer je bila njihova smerna razporeditev razdeljena po tretjinah: 25 % S-J, 40 % V-Z in 35 % diagonalno, kar predstavlja izrazito povpraševanje po diagonalnem prehajanju.

REZULTATI SPLOŠNE ANALIZE IN DOLOČITEV ROBNIH POGOJEV

Rezultati mikrosimulacij splošne analize v jutranji konici razkrivajo naravo vpliva pešcev na pretočnost kri-žišča. Kot je razvidno iz Slike 5, se pri navadnem dvofaznem križišču zamude vozil s povečevanjem obre-menitve pešcev linearno in strmo povečujejo. Pri nizki obremenitvi (100

pešcev/kra/h) znaša povprečna zamuda vozila le 16,17 sekunde (NU C), pri maksimalni obremenitvi (900 pešcev/kra/h) pa se zamuda povzpne na kar 53,72 sekunde (NU F), kar predstavlja popoln zastoj zavijalcev s kolonami dolžine preko 128 m.



Slika 6: Primerjava povprečnih zamud vozil

V nasprotju s tem so zamude vozil pri križišču s PFP skoraj povsem neodvisne od števila pešcev in ostajajo stabilno uravnotežene med 28,83 in 30,97 sekunde (NU D), ne glede na to, ali je v sistemu 400 ali 3600 pešcev/h. Razlog za to stabilnost leži v popolni časovni ločitvi faz: vozila med svojo zeleno lučjo nemoteno in neovirano zavijajo, saj so pešci varno zadržani na pločniku. Ključna ugotovitev analize je določitev točk, ki se pojavi pri obremenitvi približno 450 do 500 pešcev/kra/h (kar ustreza skupni obremenitvi okoli 1800 do 2000 pešcev/h). Nad to vrednostjo uvedba posebne faze za pešce (PFP) dejansko zmanjša zamude vozil v primerjavi s klasičnim križiščem, hkrati pa pešcem zagotavlja absolutno varnost.

Z vidika pešcev rezultati kažejo podobne zakonitosti. Pri klasičnem križišču se povprečni čas potovanja pešca zaradi konfliktov in ustavljanj povečuje. Pri križišču s PFP pa je čas potovanja pri nizkih obremenitvah nekoliko višji zaradi daljšega čakalnega časa na semaforški cikl, vendar pa z naraščanjem gostote raste počasi. Ključna prednost PFP za pešce je upad ustavitve (iz povprečnih 2,19 ustavitve pri navadnem križišču na le 1,07 ustavitve pri PFP ob diagonalnem prehodu), saj prečkajo celotno križišče v enem samem, neprekinjenem gibanju.

IMPLEMENTACIJA V SLOVENSKEM PROSTORU (PRIMER KRŽIŠČA LEDINA)

Za verifikacijo ugotovitev v realnem okolju je bilo izbrano konfliktno mestno križišče Resljeve ceste in Komenskega ulice ob gimnaziji Ledina v Ljubljani (Slika 6). To križišče zaznamujejo močni tokovi pešcev (zlasti srednješolske mladine) ter izjemno velik delež vozil, ki zavijajo levo ali desno (od 24 % do kar 60 % na po-sameznih krakih). Za potrebe validacije je bilo izvedeno štetje prometa v času popoldanske konice (med 14:30 in 15:30), ki je zabeležilo skupno 1018 pešcev/h, pri čemer pa je bilo dejansko povpraševanje po diagonalnem prehajanju relativno nizko in je znašalo le 11 % celotnega peš prometa.



Slika 7: Model za križišče Resljeve ceste in Komenskega ulice v PTV Vissim

V programu Vissim sta bila zgrajena in kalibrirana dva modela: obstoječi (dvofazni) režim in predlagani režim s PFP. Primerjalni rezultati obeh simulacij so podrobno predstavljeni v Preglednici 1.

Preglednica 1: Primerjava parametrov pretočnosti vozil in pešcev v križišču Resljeva - Komenskega

Kazalnik	Obstoječe stanje	Predlagani PFP
LOS vozil	E	E
Zamuda [s/voz]	44,72	46,41
Povp. Kolona [m]	32,70	30,93
Maks. kolona [m]	132,98	129,38
Ustavitve vozil	1553	1498
Pot. čas pešcev [s]	43,85	50,42
Ustavitve pešcev	2,19	1,97

Iz analiziranih rezultatov (Preglednica 1) je razvidno, da se po vpeljavi posebne faze za pešce prometno stanje za motorizirani promet v križišču Ledina ni bistveno spremenilo. Povprečna zamuda vozil se je minimalno povečala z 44,72 na 46,41 sekunde (povečanje za vsega 1,69 sekunde na vozilo), nivo uslug pa v obeh režimih ostaja v stabilnem razredu LOS E. Dolžine kolon in število ustavitve vozil so se v PFP režimu zaradi nemotenega zavijanja celo malenkost zmanjšale (povprečne kolone so se skrajšale z

32,70 m na 30,93 m). Tako ugoden rezultat je posledica dejstva, da se s 1018 pešci/h nahajamo točno na meji prometne obremenitve, kjer se slabosti daljšega cikla povsem kompenzirajo s prednostjo neoviranega zavijanja vozil.

Za pešce so rezultati prav tako pričakovani (Preglednica 1). Zaradi daljšega semaforkega cikla (PFP zahteva daljši skupni čas cikla za varne varovane čase prehajanja) se je povprečen čas potovanja pešca podaljšal s 43,85 sekunde na 50,42 sekunde. Vendar pa se je povprečno število ustavitv pešca zmanjšalo z 2,19 na 1,97 ustavitv (upad za 10 %), saj so lahko tisti pešci, ki so imeli željo po diagonalni poti (11 % udeležencev), križišče prečkali v enem neprekinjenem gibanju. Bistvena prednost te ureditve pa je popolna odprava konfliktnih točk (iz 24 na 0), kar varnost pešcev, zlasti šolskih otrok iz bližnjih šol, dviguje na najvišjo raven.

ZAKLJUČEK

Splošna analiza uvedbe posebne faze za pešce (PFP) je pokazala, da se prometna pretočnost za vozila in pešce v križišču načeloma poslabša. Pri izjemno visokih obremenitvah, ki presegajo 2000 pešcev na uro, smo sicer zabeležili rahlo izboljšanje pri dolžinah kolon, zamudah in številu ustavljanj v primerjavi s klasičnim križiščem, a so te razlike minimalne – gre za nekaj metrov krajše kolone oziroma nekaj sekund manjše zamude. Podoben pozitiven premik smo pri obremenitvah nad 1600 pešcev na uro opazili tudi pri povprečnem potovalnem času in zmanjšanem številu ustavljanj pešcev pri prečkanju. Glavna prednost PFP ostaja varnost, saj z ločevanjem avtomobilske in peščeve faze v celoti odpravimo konfliktno točko med njima. Čeprav tega v naši praktični analizi ni bilo mogoče neposredno potrditi, teoretična izhodišča in do-sedanje študije jasno dokazujejo njene varnostne koristi. Je pa za uspešno delovanje nujna ustrezna izo-braženost oziroma ozaveščenost udeležencev, sicer ima lahko napačna uporaba nasproten učinek.

Pričakovani so bili tudi rezultati vzpostavitve PFP na primeru izbranega križišča v Ljubljani. Kot v predhodnih analizah se je izkazalo, da nov režim nekoliko podaljša zamude. Število ustavljanj vozil je zaradi neo-viranega zavijanja (brez križanja poti s pešci) sicer manjše, se pa po drugi strani podaljša povprečni čas potovanja pešcev. Ti imajo po zaslugi možnosti diagonalnega prehajanja sicer manj vmesnih ustavljanj. V splošnem se parametri pretočnosti na ravni celotnega križišča poslabšajo, saj vpeljava dodatne faze po-daljša cikel delovanja semaforjev, kar občutno zniža nivo uslug in učinkovitost samega križišča.

Zaključimo lahko, da vpeljava PFP celostno gledano poslabša pretočnost in poveča zamude ter s tem podaljša potovalne čase vseh udeležencev. Tovrstno ureditev bi bilo zato smiselno uvajati predvsem na lokacijah z zelo močnim peš prometom (vsaj 1600 pešcev na uro v križišču). Takšen režim je priporočljiv na tistih mestih, kjer so bile v preteklosti pogoste prometne nesreče med pešci in vozili. PFP namreč učinkovito zmanjša število konfliktnih situacij in bistveno poveča varnost pešcev, kar upravičuje implementacijo tam, kjer je varnostna prioriteta višja od

zagotavljanja maksimalne pretočnosti vozil. Za sprejem optimalne odločitve pa je pred vsako preureditvijo priporočljivo izvesti podrobno mikrosimulacijsko analizo po-sameznega križišča, s katero se vnaprej preveri natančna učinkovitost in primernost takšne rešitve v danem prostoru.

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ROAD SAFETY: WEARABLE PHYSIOLOGICAL SENSORS PERFORMANCE

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Abstract

The study examines whether non-invasive psychophysiological sensors are sensitive enough to detect emotional responses to standardized visual stimuli relevant to road safety. Instead of using a driving simulator, participants viewed calibrated images with established arousal and valence values from recognized image libraries. The experimental design applies principles from traffic psychology, focusing on the role of acute emotional reactions in high-risk driving situations. A sample of nine participants ($N = 9$) was simultaneously exposed to road-related visual stimuli in a controlled classroom environment. Experimental stimuli consisted of photographs with negative valence and high arousal, whereas neutral stimuli had neutral valence and arousal. Physiological responses were measured using a wearable ring-type sensor that recorded electrodermal activity (EDA) and blood volume pulse (BVP), along with facial expression analysis via a standard web camera. A word association task captured subjective emotional responses. The primary objective was to determine whether the sensors can reliably detect momentary emotional activation. Results indicate that BVP provides rapid response dynamics, while EDA reflects slower, sustained activation patterns. Despite participant variability, preliminary findings suggest the system can detect physiologically relevant responses to emotionally charged stimuli. The study establishes methodological groundwork for future traffic safety research by validating an accessible and scalable approach for detecting emotional precursors to risky driving behavior.

Keywords:

physiological data, risk-taking behavior, road traffic safety, wearable psychophysiological monitoring

INTRODUCTION

The aim of the study is to evaluate whether wearable physiological sensors can reliably detect momentary emotional responses to standardized visual stimuli relevant to road safety. The goal was to determine the sensitivity of wearable physiological measurements in capturing variations in emotional arousal elicited by images with predefined valence and arousal levels. To do so, the typical approach is to compare different response characteristics of the measured signals, particularly the temporal dynamics of BVP (rapid changes) versus EDA (slower, sustained activation) and assess their suitability for detecting short-term emotional activation. By integrating physiological data with facial expression analysis and subjective reporting through a word association task, the study also explores a multimodal framework for assessing emotional responses,

intending to establish a methodological foundation for future research.

Traditionally, road traffic safety has been addressed through engineering, regulatory, and behavioral frameworks focusing on infrastructure design, vehicle safety technologies, and driver compliance with traffic regulations. In recent years, however, attention has been directed toward the role of human affective states in driving performance. Emotional arousal, stress, frustration, and anger can significantly influence driver decision-making, reaction times, risk perception, and vehicle control. Mentioning factors are recognized as contributors to aggressive driving behaviors and traffic conflicts, representing concerning phenomena. Aggressive driving behaviors encompasses a range of behaviors including hostile verbal reactions, tailgating, dangerous overtaking maneuvers, excessive speeding, and other forms of aggressive driving, where elevated emotional arousal impair judgment and increase the likelihood of risky driving decisions. However, identifying the onset of such states remains challenging because emotional processes often develop before observable behavioral indicators become apparent. The driver monitoring technologies have enabled continuous assessment of driver attention and vigilance through camera-based systems. Commercial platforms developed by Tobii [1] and iMotions [2] demonstrate how eye tracking, gaze estimation, blink dynamics, and head-pose analysis are integrated to evaluate driver state in real time [3].

In last few years, physiological sensors in automotive contexts have become a core component of broader Driver Monitoring Systems (DMS), which integrate computer vision, and dedicated sensing technologies—most notably infrared (IR) cameras—to assess driver state in real time [4]. The systems exploiting infrared illumination reflected from the cornea and pupil achieve gaze detection under varying lighting conditions [5]. Computer vision algorithms extract facial and ocular features such as pupil position, eyelid openness, blink rate, gaze direction, and head movement. The parameters are later used to infer levels of attention, fatigue, and distraction (vir: tobii). The implementations rely on machine learning and neural networks that process signals in real time, identifying behavioral patterns associated with drowsiness or cognitive disengagement. The typically adopted metric is PERCLOS (Percentage of Eye Closure), which measures the proportion of time a driver's eyes remain closed and is considered a reliable indicator of fatigue [6]. When thresholds are exceeded, the system can trigger warnings.

The measuring design consists of facial landmark detection, gaze estimation, fatigue detection, and behavioral analysis, combining RGB and infrared sensing modalities, to ensure reliable performance across diverse environmental conditions. In the next step, the DMS technologies operate in conjunction with Advanced Driver Assistance Systems (ADAS), where gaze data is fused with environmental sensing to determine whether the driver has perceived critical hazards [7]. Although such technologies are theoretically expected to reduce accident risk through continuous monitoring of driver attention, empirical evidence suggests that their effectiveness in real-world scenarios remains subject to ongoing evaluation [8].

Despite integration into vehicles as incremental safety enhancements, the DMS technologies have attracted relatively limited public debate. The reason is probably that mentioning systems operate largely invisibly and passively, which reduces user awareness. From a regulatory perspective, the European Union has incorporated DMS into its General Safety Regulation, making such systems mandatory for new vehicles as of July 2024 [9]. The requirement was introduced alongside other safety features, thereby minimizing its visibility as a distinct policy issue. The regulatory justification is rooted in road safety: human error, including fatigue and distraction, remains a leading cause of traffic accidents. Consequently, continuous monitoring of driver attention is framed as a necessary intervention aligned with broader policy initiatives such as the EU's "Vision Zero" strategy to eliminate road fatalities [10]. At the same time, the mentioning framing shifts the public discourse away from concerns about surveillance and privacy. The use of eye-tracking systems raise important questions regarding data protection, particularly under the General Data Protection Regulation (GDPR). Since DMS processes physiological signals, it potentially falls within the category of sensitive personal data. In theory, however, most automotive implementations rely on local, in-vehicle processing without transmitting or storing identifiable data, thereby limiting the scope of personal data processing. The GDPR permits such processing when it is strictly necessary for system functionality and adheres to principles of data minimization and transparency [11]. Thus, manufacturers address GDPR requirements through ephemeral data handling and user disclosures within vehicle documentation or settings interfaces [12].

In practice, advanced sensing hardware, computational modeling (e.g., pupil center corneal reflection methods), and multimodal data integration can be combined to deliver real-time assessments of driver state. By integrating metrics like PERCLOS with other behavioral indicators—including blink dynamics, gaze patterns, and head movements—the system employs classification models, based on neural networks, to evaluate driver's attention continuously. Despite advances, current DMS technologies primarily focus on attentional processes and vigilance. Comparatively little focus has been devoted to emotional states that may impair driving performance. Existing camera-based systems may observe behavioral manifestations of anger but fail to capture the underlying physiological activation that precedes overt behavioral responses.

Recent developments in wearable biosensors provide an opportunity to address this limitation. Electrodermal activity reflects changes in skin conductance caused by sympathetic nervous system activation, and has long been recognized as a sensitive indicator of emotional arousal, stress, and attentional engagement. Importantly, EDA does not identify specific emotions; rather, it measures the intensity of autonomic activation. Similarly, Blood Volume Pulse, typically obtained by smartwatch, provides information about cardiovascular dynamics including heart rate variability. Rapid changes in BVP-derived measures have been associated with acute stress responses and emotional reactivity. Compared with EDA, BVP often exhibits faster transient responses, whereas electrodermal responses may develop more gradually and persist longer following emotionally salient events. The simultaneous assessment of EDA and BVP offers information regarding the temporal dynamics of emotional activation, relevant in driving environments where sudden provocations, traffic conflicts, or perceived violations by other drivers may trigger rapid physiological responses. Integrating such measurements with traditional DMS inputs may enable earlier detection of emotionally charged driving situations and support adaptive interventions aimed at reducing accident risk.

The present research does not aim to identify specific psychological disorders or personality. It focuses on assessing whether wearable sensors can reliably detect physiological responses to emotionally salient stimuli and whether these measurements can enhance existing driver monitoring systems. Within framework, the objective is to evaluate sensor responsiveness and signal quality. The contribution lies in validating whether modern wearable sensors possess sufficient sensitivity, reliability, and temporal resolution for real-world deployment. If successful, integrating physiological sensing into Driver Monitoring Systems could provide a novel pathway toward identifying and mitigating emotional risk factors associated with aggressive driving behaviors.

EXPERIMENTAL DESIGN

The study adopts a multimodal psychophysiological measurement approach to investigate potential early indicators of emotional distress in road traffic environments. The experimental setup combines non-invasive physiological sensing with visual and contextual monitoring. Participants are equipped with a wearable biometric ring (SensRing), which enables continuous acquisition of electrodermal activity (EDA), photoplethysmography (PPG), and skin temperature (**Figure 1**). EDA is used as an indirect indicator of sympathetic nervous system activation and reflects changes in psychological arousal, stress, and emotional reactivity. The PPG signal provides heart rate (HR) and heart rate variability (HRV), which are associated with autonomic regulation and cognitive load, while skin temperature serves as a slower-changing physiological baseline indicator. In parallel, participants are recorded using a frontal camera to capture facial expressions. Facial data are analyzed using the Affectiva facial expression software, where specific facial expressions correspond to certain

emotional states (**Figure 2**). The integration of physiological and facial data enables an interpretation of internal states, as physiological signals alone do not always capture the qualitative dimension of emotional experience.

The experiment was carried out in three phases: first, a baseline phase to record participants' normal physiological state; second, an experimental phase where they were exposed to selected stimuli; and throughout both phases, participants also completed a word association task, where they responded with the first word that came to mind whenever a stimulus appeared. The word association task helps to understand what increased arousal means; whether a stronger physiological reaction is linked to fear, discomfort, or reveal biases or emotionally loaded thoughts, which suggests an underlying emotional reaction that participants might not express directly.

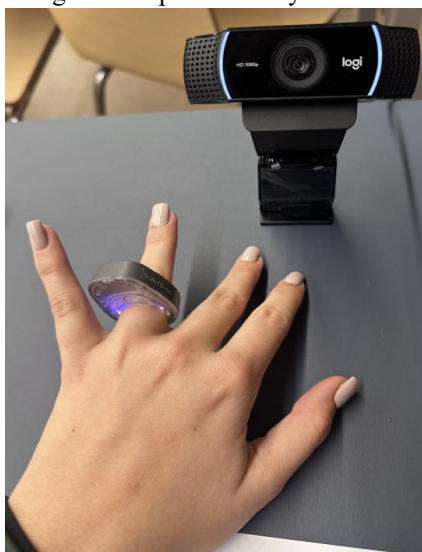


Figure 1: Each participant was equipped with EDA sensor, and standard web camera for face recording.

In the second phase, participants are exposed to a sequence of standardized visual stimuli with varying emotional valence and arousal levels. Each stimulus is presented for a fixed duration (e.g., 8 seconds), while physiological responses are continuously recorded.

Throughout the experiment, all sensor data are time-synchronized with event markers, enabling precise alignment between stimuli, behavioral responses, and physiological changes. The signals are later preprocessed to remove noise and artifacts using filtering and averaging. Time-series analysis is used to examine signal dynamics, while event-based analysis focuses on physiological responses immediately following stress-inducing stimuli. Data processing and analysis are conducted using Python-based scripts, with pandas and matplotlib libraries for data handling and visualization.

The overall objective is identification of early psychophysiological markers that may precede unsafe behavior in traffic. By detecting elevated response, reduced attentional control, or prolonged reaction time, such systems could contribute to the development of adaptive and preventive driver assistance technologies.

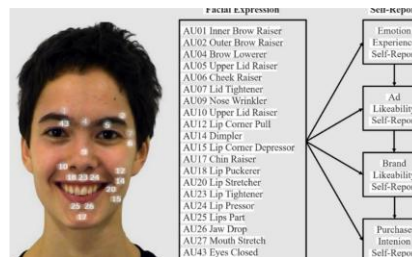


Figure 2: Affectiva software for facial expressions.

RESULTS AND DISCUSSION

The experimental setup simulated a driver's perspective by presenting a visual image, resembling a view through a car window. Images of landscapes, roadside environments, animals, and human figures were projected in sequence, creating a dynamic but controlled approximation of real-world traffic surroundings. The stimuli were selected from the Open Affective Standardized Image Set (OASIS) (vir), which provides normative ratings of valence and arousal. The standardization enabled a priori expectations regarding the emotional and physiological responses associated with each image category.

The average physiological EDA response (Figure 3) indicates a pronounced peak at timestamp 19:10:06, corresponding to the stressor, where electrodermal activity exhibited a sharp increase.

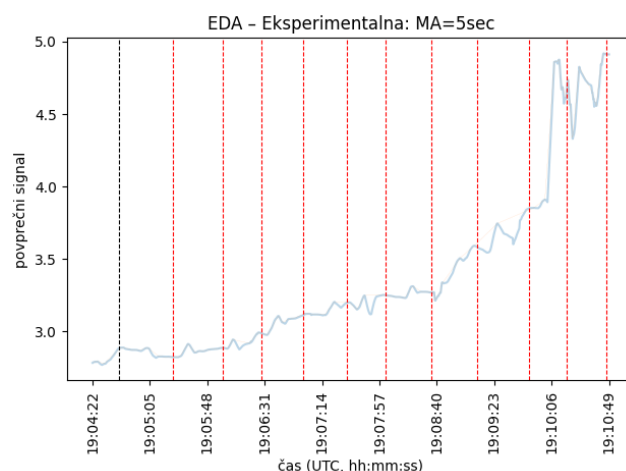


Figure 3: Corresponding to the stressor, average physiological EDA response showing a peak at 19:10:06,

The processed blood volume pulse signal (Figure 4) showed at the same time a decrease in amplitude, potentially indicating a fight-or-flight response. The pattern is consistent with acute sympathetic nervous system activation. The rapid rise in EDA reflects increased eccrine sweat gland activity driven by heightened arousal, while the reduction in BVP amplitude suggests peripheral vasoconstriction, commonly associated with stress-related cardiovascular responses. From a physiological standpoint, the response indicates a sudden increase in arousal and environmental salience. While such patterns are commonly associated with acute responses, in the broader context of affective and cognitive

processing they may also reflect states of heightened internal tension, emotional overload, or narrowing of attentional focus.

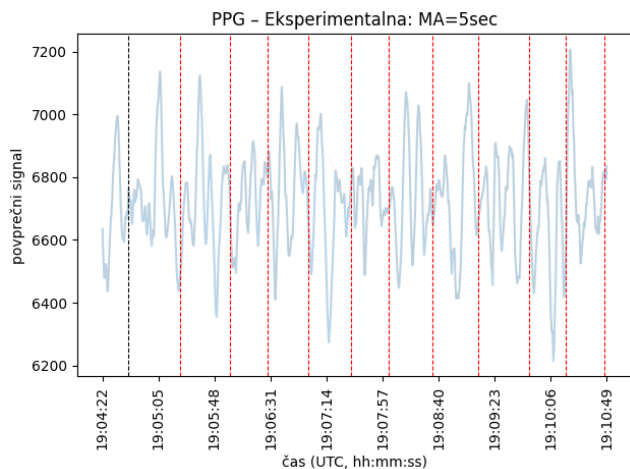


Figure 4: The trend.

It is important to emphasize that a single physiological response of this kind cannot be interpreted as evidence of emotional risk factors associated with aggressive driving behaviors, however, repeated patterns characterized by high arousal, reduced physiological variability, and convergence with negatively valenced responses may indicate a state of emotional activation, where other drivers may trigger rapid physiological responses. The predictive value of the responses is not in single events, but in patterns over time, detecting shifts toward higher stress. When combined with context and behavior data, such systems may help identify drivers at risk of impaired decision-making.

In the final part of the study, participants completed a survey questionnaire designed to assess their exposure to Driver Monitoring Systems (DMS) in real-world driving contexts. The survey collected a total of 29 responses. Seven respondents reported having prior experience with a vehicle equipped with a DMS, while the majority indicated no direct exposure to such systems, suggesting that DMS remains a developing feature in everyday driving contexts rather than a widely established standard. A majority of respondents (71%) viewed DMS positively and considered the system beneficial for road safety. In contrast, 14% identified privacy concerns, while another 14% perceived the system as intrusive during everyday driving. The distribution suggests an overall favorable perception of DMS, although concerns remain primarily related to privacy and the feeling of being constantly monitored.

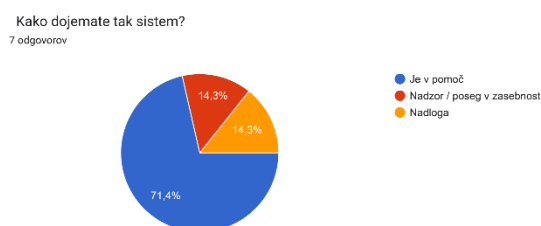


Figure 5: Distribution of participant attitudes toward DMS.

A majority (71%) viewed the system as beneficial, 14% considered a privacy concern, while another 14% perceived it as intrusive during everyday driving.

More than half of the respondents reported that DMS alerts were disturbing or disruptive during driving (Figure 6). In addition, participants frequently noted a mismatch between system warnings and their perceived level of attention, suggesting potential issues with the sensitivity or calibration of the detection algorithms, indicating that while alert systems are designed to enhance safety, excessive or inaccurate warnings may reduce user trust and lead to alert fatigue, potentially diminishing their effectiveness in real-world conditions.

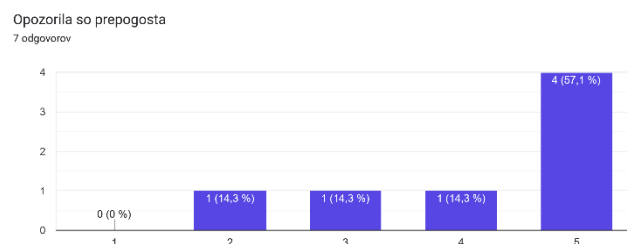


Figure 6: User evaluation of DMS warning systems. More than half of the respondents perceived alerts as disturbing, reporting that the warnings often fail to correspond to their actual level of attention.

When considering the potential safety benefits of AI-based Driver Monitoring Systems, respondents without prior experience with DMS were more likely to express optimism about their effectiveness (Figure 7). Participants believed that such systems could help prevent serious driver-related accidents, including incidents that have recently gained public attention on Slovenian motorways (vir). Although the sample does not provide evidence of actual system effectiveness, it reflects a public trust in AI-supported safety technologies. At the same time, it also suggests that expectations may be influenced by high-profile road safety events and broader confidence in artificial intelligence as a preventive tool.

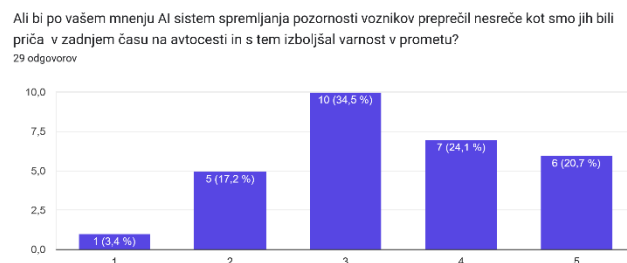


Figure 7: Distribution of responses concerning the potential safety benefits of AI-based Driver Monitoring Systems. Notably, respondents without prior experience to DMS

technologies frequently reported that such systems could help prevent serious driver-related accidents

CONCLUSIONS

The identification and the interpretation of early psychophysiological markers that may precede unsafe behavior in traffic is possible but requires caution, as autonomic arousal is inherently non-specific and cannot be directly attributed to a single psychological state without considering broader psychological and situational context. In the present case, the observed response profile is consistent with a fight-or-flight reaction, characterized by a shift toward sympathetic nervous system dominance. The triggering stimulus at this moment was likely perceived as salient or potentially threatening, leading to rapid cognitive appraisal of environmental demands. From a physiological perspective, the response reflects increased vigilance and preparatory action, including autonomic adjustments such as altered cardiovascular activity and redistribution of blood flow, which together support rapid behavioral readiness in response to perceived risk, suggesting that physiological monitoring may provide useful insights into cognitive states relevant to driving behavior. The integration into driver monitoring systems could improve the detection of acute stress or emotional states that may impair decision-making and reaction time. However, translating physiological data into reliable behavioral inference remains challenging, since similar autonomic patterns may be associated with different emotional or cognitive states. For this reason, multimodal approaches combining physiological, behavioral, and contextual data are likely necessary to improve interpretability and reduce ambiguity, extending beyond traditional disciplinary boundaries, connecting transportation engineering, forensic science, and clinical psychology. Also, existing research addresses associations between severe risk outcomes and demographic or clinical variables, as human behavior is dynamic, context-dependent, and subject to rapid change over time.

Real-time physiological monitoring using wearable or in-vehicle sensor technologies therefore represents a promising approach for capturing transient risk states. At the same time raises important ethical and legal questions regarding data protection. Driver Monitoring Systems process physiological signals, falling within the category of sensitive personal data, and as such can be used to infer an individual's physical and mental state. Furthermore, the use of such systems introduces concerns about autonomy and surveillance. Also, the potential consequences of false-positive classifications raise significant ethical issues, as incorrect detection of risk states could lead to unnecessary interventions, driver distraction, or even unfair profiling.

In conclusion, road traffic accidents reflect the interplay of behavioral, psychological, forensic, and transportation-related factors. Future research will focus on developing classification frameworks, conducting longitudinal

investigations of psychophysiological factors, and ensuring the ethical integration of sensor-based monitoring technologies. Effective prevention strategies will require an interdisciplinary approach that integrates engineering, psychiatry, and data science to address both systemic conditions and individual risk factors.

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INFORMATION AND DATA REQUIREMENTS FOR REMOTE MARITIME PILOTAGE: A PILOT-CENTRED PERSPECTIVE

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Abstract

Remote maritime pilotage is increasingly recognized as a potential component of future digital maritime operations. While previous studies have primarily focused on technological feasibility, communication systems, and regulatory challenges, considerably less attention has been devoted to identifying the information maritime pilots require to support safe and effective decision-making in a remote operational environment. This paper adopts a pilot-centred perspective and examines the information requirements for remote pilotage. Drawing on recent research and operational knowledge from maritime pilotage, it proposes a conceptual framework that classifies pilot information requirements into five categories: navigational, environmental, operational, communication, and perceptual information. For each category, the paper discusses its role in pilot decision-making, the availability of corresponding digital data sources, and the current limitations of remote information delivery.

The analysis indicates that the successful implementation of remote pilotage depends not only on technological advances but also on the completeness, quality, reliability, and integration of information available to the pilot. Particular challenges remain in replicating perceptual information and maintaining situational awareness outside the onboard environment. The proposed framework provides a structured basis for future research on remote pilotage systems and supports the development of human-centred digital solutions for maritime navigation.

Keywords:

remote maritime pilotage; information requirements; pilot-centred approach; situational awareness; decision support

INTRODUCTION

Maritime pilotage is an essential component of navigational safety in ports, confined waters and other operationally demanding environments. Maritime pilots provide specialized local knowledge and ship-handling expertise, supporting shipmasters during maneuvers that may involve restricted waterways, dense traffic, limited under-keel clearance and challenging environmental conditions. Their decisions rely on the continuous assessment of the vessel's movement, the surrounding environment and the operational circumstances in which the maneuver takes place.

In conventional pilotage, the pilot is physically present on board and works in close cooperation with the master and bridge team. This arrangement provides direct access to navigational instruments, visual observations,

communications and information exchanged during bridge operations. Modern pilotage increasingly relies on radar, the Automatic Identification System (AIS), Electronic Chart Display and Information Systems (ECDIS) and Portable Pilot Units (PPUs). Nevertheless, these technologies constitute only part of the information environment within which pilots operate.

Pilots also interpret a vessel's behavior through direct observation, local knowledge, and continuous interaction with other participants. During a berthing maneuver, for example, a pilot must consider the vessel's position, heading, and speed, along with its lateral movement, the effects of wind and current, the availability of tug assistance, and the vessel's proximity to the berth. These elements are integrated into an understanding of the developing situation, which supports the selection and timing of navigational actions.

Digital transformation in the maritime sector has created opportunities to reconsider how navigational services are delivered. Advances in communication infrastructure, sensor technologies, data integration, and remote monitoring have contributed to growing interest in remote maritime pilotage. Remote pilotage generally refers to an arrangement in which pilotage-related navigational guidance is provided from outside the vessel, typically from a shore-based facility. The remote pilot may receive navigational data, environmental measurements, and video streams while communicating with the bridge team and other shore-based participants.

Existing research has examined technological approaches, operational arrangements, visual perspectives and situational awareness in remote pilotage (Lahtinen et al., 2020; Kato and Horiguchi, 2022; Grundmann et al., 2023; Ujkani et al., 2024; Törmä et al., 2025). A previous systematic literature review by Glišović and Krmac (2026) identified 23 studies for qualitative synthesis, including 19 core studies specifically addressing remote pilotage. It organized the literature into technological, operational, safety, human-factor and legal or regulatory domains. These research domains do not, however, directly specify the information required for individual pilotage tasks.

A vessel's position, heading, speed, and rate of turn may be available through electronic systems, yet these parameters do not always provide a complete picture of its behavior during a complex maneuver. Their operational meaning depends on the surrounding circumstances and the decisions the pilot must make.

Remote pilotage is not simply about transferring navigational data from a vessel to a shore-based station. It is about ensuring that the pilot receives the right information at

the right time and in a form that supports safe navigational decisions.

The relationship between information requirements and navigational decision-making has been examined in maritime research. Sharma et al. (2019) used goal-directed task analysis to investigate information requirements for situation awareness. This task-oriented perspective is relevant to remote pilotage, where information ordinarily obtained through physical presence may need to be delivered or interpreted in different ways.

The study addresses three research questions: RQ1: What are the key information requirements for safe and effective remote maritime pilotage? RQ2: What challenges and limitations arise when providing these information requirements in a remote operational environment? RQ3: How can the identified information requirements be integrated into a pilot-centred conceptual framework to support situational awareness and navigational decision-making in remote maritime pilotage?

The contribution lies in linking information requirements to pilotage tasks, potential sources, and the limitations of remote delivery. Rather than starting with available technologies, the proposed framework places operational needs at the center of the analysis.

METHODOLOGY

Research approach

This study uses a qualitative, literature-informed conceptual approach to examine the information and data requirements associated with remote maritime pilotage. It builds on a previous PRISMA-based systematic literature review by Glišović and Krmac (2026), which searched Scopus and ScienceDirect for research published between 2010 and January 2026 and identified 23 studies for qualitative synthesis, including 19 core publications that specifically address remote pilotage.

The earlier review classified research into technological enablers, operational frameworks, safety and risk assessment, human factors, and legal and regulatory considerations. The present paper adopts a different perspective: it examines the information needed to perform pilotage tasks rather than the research domains to which publications belong. This is a conceptual reinterpretation of relevant literature, not a new systematic review or an empirical study.

Identification and classification of information requirements

Information requirements are considered in relation to monitoring vessel movement, assessing navigational hazards and environmental influences, planning and coordinating maneuvers, communicating instructions and interpreting spatial relationships. The distinction between data and operationally meaningful information is central: a rate-of-turn reading, for example, becomes useful when interpreted against intended vessel movement, available turning space and nearby hazards.

Five categories are proposed according to the primary operational function of the information: navigational, environmental, operational, communication and perceptual. They are not mutually exclusive. A camera image may serve a perceptual function while also supporting navigational assessment; a conversation with a tug operator may convey both operational status and confirmation of instructions.

The conceptual development considers each category's operational purpose, potential shipboard or shore-based sources and foreseeable limitations of remote delivery. Professional pilotage experience informs the interpretation of practical tasks but is not presented as independently collected empirical evidence. The classification has not been validated through interviews, surveys, simulations or operational trials.

Framework development and analytical boundaries

The proposed framework links pilotage tasks with information requirements, potential sources, information quality, situational awareness, and navigational decision-making. Accuracy, completeness, timeliness, reliability, integrity, and integration are treated as cross-cutting properties rather than separate information categories.

A fully reproducible study-to-requirement extraction matrix is still needed before the conceptual classification can be described as the outcome of completed full-text coding. Accordingly, the present findings are presented as propositions informed by selected literature and operational reasoning, not as measured effects or validated requirements.

RESULTS: PROPOSED INFORMATION REQUIREMENTS

The proposed classification is summarized in Table 1 and described in detail in the following sections.

Category	Examples	Potential sources	Primary limitation
Navigational	Position, heading, SOG, STW, ROT, UKC, traffic	GNSS, radar, AIS, ECDIS, PPU	Accuracy, latency, integrity
Environmental	Wind, current, visibility, water level	Weather and hydrographic sensors	Local representativeness
Operational	Berth readiness, tugs, mooring, traffic	VTS, port and terminal systems	Fragmentation, timeliness
Communication	Instructions, acknowledgements, updates	VHF, voice, video, data links	Delay, ambiguity, interruption
Perceptual	Visual references, relative movement, motion cues	Cameras, positioning and displays	Viewpoint, sensory limitations

Table 1: Proposed classification of information requirements (Source: Authors proposed conceptual classification; not empirically validated).

Navigational information

Navigational information supports assessment of a vessel's position, movement, and relationship to hazards and surrounding traffic. Relevant parameters include position, heading, course over ground (COG), speed over ground (SOG), speed through water (STW), rate of turn (ROT), under-keel clearance (UKC), traffic movements,

navigational marks, and available maneuvering space. GNSS, radar, AIS, ECDIS, and PPUs provide potential data sources (Grundmann et al., 2023; Ujkani et al., 2024).

The usefulness of these measurements depends on accuracy, update frequency, latency, and integrity. During final berthing, longitudinal movement, lateral displacement, and rotation must be assessed together. Isolated numerical readings may be insufficient to represent combined vessel motion. Conflicting sensor data or interrupted communications can further undermine confidence. Work on land-based sensing for remote operators is relevant to independent verification of movement information (Louédec et al., 2025). The requirement is therefore not simply to transmit parameters, but to enable a sufficiently reliable interpretation of movement for the task at hand.

Environmental information

Environmental information describes external influences on vessel handling, including wind, current, visibility, water level, tides, and sea conditions. The importance of each parameter varies with vessel characteristics, geography, and maneuver. At low speeds, external forces may become especially relevant to the pilot's assessment of control margins.

Remote operations may rely on meteorological stations, current sensors, water-level gauges, and port monitoring infrastructure. However, a measurement taken at a fixed location may not represent the conditions affecting the vessel. Cranes, buildings, and shoreline geometry can create local wind effects, while current conditions may vary across a harbor basin. Lahtinen et al. (2020) provide relevant context for considering operational conditions within an intelligent fairway. The central information requirement is therefore the provision of measurements whose spatial and temporal relevance can be assessed for the vessel's actual maneuver.

Operational information

Operational information concerns berth readiness, traffic movements, tug allocation, mooring arrangements, port restrictions and the timing of coordinated activities. These details shape how and when navigational actions can be carried out. A berthing strategy may depend on tug positioning, while a change in mooring readiness may alter the timing of the final approach.

Such information is often distributed across VTS, terminal systems, port authorities and direct communications. Remote pilotage may increase dependence on timely exchange between organizations. Fragmented systems and delayed updates can make the operational picture incomplete. Work examining remote pilotage as a coordinated activity is pertinent to this concern (Praetorius and Sharma, 2025). Operational information merits a distinct category because safe decisions depend not only on vessel movement but also on whether the wider operation is ready to support the maneuver.

Communication information

Communication supports the exchange of orders, confirmations, observations, and operational updates among the pilot, master, bridge team, VTS, tugs, and mooring personnel. When the pilot is ashore, reliable communication becomes the principal means of maintaining coordination with those executing maneuvering instructions on board.

Voice, VHF, video, and digital messaging can each contribute, but connection availability alone is insufficient. Clarity, timing, acknowledgment, and shared understanding matter. Closed-loop confirmation can reduce uncertainty about critical orders. Remote arrangements may also reduce access to informal bridge exchanges and nonverbal cues. Communication information is therefore defined by its role in coordination and confirmation, not merely by the technical channel through which a message passes.

Perceptual information

Perceptual information comprises visual references, spatial orientation, relative movement, and motion-related cues used to interpret vessel behavior. On board, a pilot can observe the vessel's position relative to a quay and combine that observation with instrument readings and physical cues. Remote pilotage changes this perceptual setting.

Camera systems, positioning sensors, and visualization tools may provide functional alternatives, but viewpoint, field of view, image quality, lighting, and depth perception can affect interpretation. Kato and Horiguchi (2022) examined differences associated with first- and third-person perspectives in ship handling; Ujkani et al. (2024) and Törmä et al. (2025) address relevant aspects of visualization and shared situational awareness.

The objective does not need to be to recreate every sensory feature of the bridge. A more useful question is which operational judgment a cue supports and whether an alternative combination of measurements and displays can support that judgment. For instance, relative position measurements and camera views might jointly assist the assessment of lateral motion alongside a berth. Whether such alternatives are sufficient must be tested rather than assumed.

Integrated conceptual framework

The proposed framework (see Figure 1) begins with pilotage tasks and the decisions they entail. These tasks determine information requirements, organized into five interacting categories. Shipboard sensors, shore-based infrastructure, port systems, and communications may supply the relevant data. Their usefulness depends on accuracy, completeness, timeliness, reliability, integrity, and integration. The resulting information may support situational awareness and, in turn, navigational decision-making.

Requirements also vary with the phase of pilotage. During channel transit, traffic, position, depth, and environmental conditions may dominate. During berthing, lateral movement, distance from the quay, tug coordination, and mooring readiness may become more important. The framework does not prescribe equal priority or continuous

presentation for all data. It provides a task-oriented basis for evaluating what information should be available and when.

Figure 1. Pilot-centred logic of the proposed information requirements framework

Conceptual relationships only; improved safety is not demonstrated by this framework.

PILOTAGE TASKS
Operational goals, manoeuvres and decisions
INFORMATION REQUIREMENTS
Navigational · Environmental · Operational · Communication · Perceptual
SOURCES AND DELIVERY
Shipboard sensors · Shore-based sensors · Port systems · Communication
CROSS-CUTTING INFORMATION QUALITY
Accuracy · Completeness · Timeliness · Reliability · Integrity · Integration
SITUATIONAL AWARENESS
Interpretation of the current and developing navigational situation
NAVIGATIONAL DECISION-MAKING
Selection, coordination and timing of pilotage actions

Figure 1. Pilot-centred conceptual framework

DISCUSSION

4.1 From data availability to operational requirements

The framework distinguishes between the ability to transmit data and the ability to support a decision. Position, heading, and rate-of-turn measurements may be continuously available without fully conveying how a vessel is moving relative to a berth. The operational question is whether the pilot can interpret these parameters alongside environmental conditions, tug actions, and visual references.

A task-first design approach therefore begins by identifying the decisions required during each phase of pilotage and then specifying the information needed to make them. Accuracy, timeliness, and reliability should be assessed in context: a delay in berth-planning information has different implications than a delay in movement information during close-quarters maneuvering. The proposed categories are useful to the extent that they make these differences explicit.

Perception and situational awareness

Physical separation alters the pilot's access to visual, spatial, and motion-related cues. It also changes how information is shared with the bridge team. Digital displays and camera views may support situational awareness, but they do not automatically reproduce the perceptual context of being on board. Their effectiveness depends on whether they provide the cues needed for a particular judgment.

A remote pilot may need to monitor several screens while communicating with the bridge team, VTS, and tugs. Poorly organized interfaces may impose additional attentional demands. Accordingly, interface design should consider how information is prioritized, integrated, and made available during time-critical maneuvers. These are hypotheses for future assessment, not demonstrated performance outcomes of the proposed framework.

Implications for human-centred design

The framework suggests that remote pilotage systems should be evaluated against operational tasks rather than the

number of sensors or displays installed. A coherent picture may require navigational, environmental, operational, communication, and perceptual information to be interpreted together. This does not imply that all data must be shown continuously. The most relevant information can change between transit, turning, and berthing phases.

System requirements should also address degraded information. When a measurement is delayed, inconsistent, or unavailable, the pilot needs a means of recognizing the limitation and determining whether the operation can continue safely. The appropriate technical safeguards and operational procedures will depend on the task, local conditions, and the allocation of responsibilities between shore and vessel.

Limitations and future research

This study is conceptual and grounded in the literature. It does not establish the relative importance of individual requirements, demonstrate the adequacy of alternative sensory cues, or validate the framework across ports and vessel types. Its categories are an analytical proposal, not a definitive taxonomy.

Future work should document full-text evidence extraction for each requirement, consult experienced pilots and relevant operational stakeholders, and examine differences between pilotage phases. Interviews and Delphi studies could refine the classification, and simulator studies could test the influence of information availability and interface design on situational awareness, workload, and decision-making. Such validation would be necessary before translating the framework into prescriptive technical or operational standards.

CONCLUSIONS

This paper proposed a pilot-centered classification of information requirements for remote maritime pilotage. In response to RQ1, it identified five interconnected categories: navigational, environmental, operational, communication, and perceptual information. Each contributes to the pilot's understanding of vessel movement and the operational circumstances in which decisions are made.

Regarding RQ2, the analysis highlighted challenges related to accuracy, timeliness, integrity, integration, and the reduced availability of direct perceptual cues. Digital access to measurements alone cannot be assumed to provide adequate operational understanding.

In response to RQ3, the proposed framework links pilotage tasks with information requirements, potential sources, cross-cutting information quality, situational awareness, and navigational decision-making. It offers a structured basis for future research but has not yet been empirically validated. Interviews, expert consensus methods, and simulation are needed to refine the classification and test its usefulness.

Ultimately, remote pilotage should be developed around the information needed for safe decisions, rather than simply around the technologies capable of transmitting data ashore.

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THE USE OF UNMANNED AERIAL SYSTEMS IN STATE OPERATIONS: ANALYSIS OF LEGISLATION AND BEST PRACTICES ABROAD AND COMPARISON WITH THE CURRENT STATE IN SLOVENIA

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Abstract

EU legislation does not specifically regulate the use of unmanned aerial systems in national operations; therefore, Member States retain sovereignty in this area.

However, they are well-advised to apply the relevant EU legislation also for state operations, in part to promote harmonisation between member states but also because the EU legislation is already well developed and detailed. At the same time, there is a growing convergence between EU civil legislation and NATO military standards. In both cases, the legislation aims to manage risks during the conduct of operations, with these risks being determined by crew qualifications, the complexity of UAVs, and the nature of the operations. We analysed the relevant EU legislation and adopted NATO standards, as well as existing examples of best practices in several selected European countries. Based on all of this, we have developed guidelines that can serve as a foundation for regulating this area in Slovenia in the future.

Keywords

unmanned aerial systems, state operations, UAS regulation, EU legislation, NATO standards

INTRODUCTION

Unmanned aerial systems (UAS) are increasingly used by state operators - armed forces, police, firefighting and civil-protection services - for tasks ranging from surveillance to disaster response. Their integration into national airspace, however, must not compromise the safety of other airspace users, which is a particular concern in small and densely used airspace systems such as Slovenia.

A defining feature of this field is that EU aviation legislation does not, in principle, apply to state operations: Regulation (EU) 2018/1139 explicitly excludes military, customs, police, coastguard and similar activities from its scope, leaving Member States sovereign over their state aircraft [1]. The same regulation, however, allows a Member State to opt in and voluntarily apply parts of the civil framework to state activities. In parallel, NATO has developed its own family of standardisation agreements (STANAG) for UAS airworthiness, operation and crew qualification, and recent editions of these standards show a clear tendency to converge with the civil EU risk-based approach.

This paper examines why and how state UAS operations can be aligned with EU civil legislation and NATO standards even though this is not legally required, reviews how several European countries have addressed this question in practice,

and compares these findings with the situation in the Republic of Slovenia. Building on a related, more detailed regulatory gap-analysis of the Slovenian framework [2], the present paper focuses on the broader European regulatory landscape and distils the resulting guidelines that could inform future Slovenian legislation. The analysis follows a qualitative comparative approach: the relevant EU regulations and NATO standardisation agreements were identified together with publicly available national military UAS regulations in the United Kingdom, Germany and the Netherlands, chosen for their mature, publicly documented and risk-based frameworks; their common structural elements were then contrasted with the Slovenian regulatory landscape to derive transferable guidelines.

EU LEGISLATIVE FRAMEWORK FOR STATE UAS OPERATIONS

Regulation (EU) 2018/1139 sets the boundaries of EU competence in aviation safety and lists military, customs, police, coastguard, firefighting and similar activities among those to which the common rules do not automatically apply [1]. Article 2(6) nevertheless gives Member States an explicit opt-in: a state may decide that some or all of the safety rules for civil UAS should also govern some or all of its state activities and personnel competence. This opt-in is central to our analysis, because it means that the choice of regulatory model for state UAS is, above all, a national policy decision rather than a legal obligation.

The civil framework that a state may draw on is well developed. Commission Implementing Regulation (EU) 2019/947 defines Open, Specific and Certified operational categories linked to operational risk, together with the corresponding authorisation procedures [3], while Delegated Regulation (EU) 2019/945 sets product and class-marking requirements for the UAS themselves [4]. Implementing Regulation (EU) 2021/664 further defines the U-space regulatory framework for the safe management of increasingly dense low-altitude UAS traffic [5], an environment in which state and civil operations will increasingly compete for the same volume of airspace.

Applying this framework, or its risk-based logic, to state operations offers three practical advantages. First, it re-uses a mature, extensively tested body of rules instead of requiring each country to design its own rules. Second, it harmonises the treatment of state UAS across Member States, which simplifies cross-border operations, exercises

and mutual assistance. Third, it eases the interface between state and civil operators sharing the same airspace, since both sides work from comparable risk categories and comparable evidence requirements.

The Article 2(6) opt-in in the Regulation (EU) 2018/1139 is not an all-or-nothing choice: a state may apply only selected sections of the civil rulebook, to only some of its state activities, and can therefore introduce the risk-based model gradually, for example, starting with training and airworthiness while keeping airspace-access rules under separate national control, or applying it first to protection-and-rescue operators before extending it to defense operations. This flexibility is one of the main reasons why the national frameworks reviewed in Section 4 differ in scope even though they share the same underlying logic.

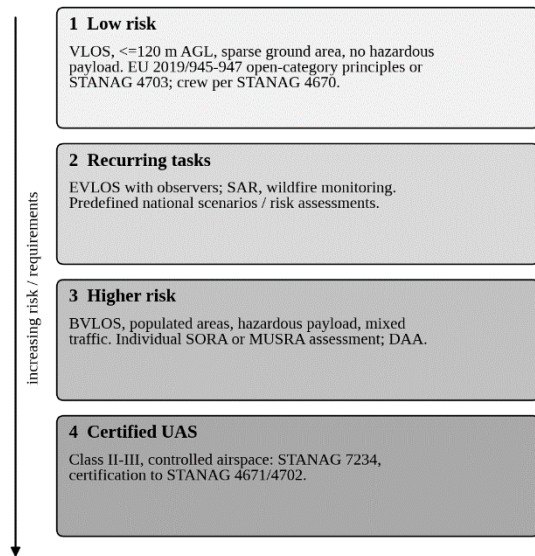


Figure 1: A generic risk-based tiering of state UAS operations, combining EU (SORA, STS/PDRA) and NATO (MUSRA, STANAG 7234) principles.

NATO STANDARDS AND RISK-ASSESSMENT METHODOLOGIES

NATO standardisation agreements (STANAG) [6] address the same problem from the military side. STANAG 4671, 4702 and 4703 provide airworthiness requirements for, respectively, large fixed-wing, rotary-wing and light UAS [7-9]. STANAG 4670 defines competency-based training and qualification requirements for UAS crews [10]; and STANAG 7234 addresses the integration of large military UAS into airspace on principles comparable to manned aviation [11]. None of these standards is directly applicable national law - they become binding only once a state incorporates them, by reference or otherwise, into its own regulation.

Both the EU and NATO regimes are, at their core, risk-based: the applicable requirements scale with the danger an operation poses to people on the ground and in the air. On the civil side this is operationalised through the Specific Operations Risk Assessment (SORA 2.5) [12], which derives mitigation measures from airspace class, ground-area characteristics and human exposure. Its military

counterpart, the Military UAS Specific Risk Assessment (MUSRA), extends the same logic with mission-specific and payload-specific factors [13]. Figure 1 summarises how operational risk drivers - flight mode, ground area and airspace class - translate into an increasingly demanding set of regulatory requirements.

BEST PRACTICES IN SELECTED EUROPEAN COUNTRIES

Several European states have translated the EU/NATO risk-based logic into their national UAS military rules. The United Kingdom regulates military UAS operations through Regulatory Article (RA) 1600, which defines a set of operational categories with clearly stated conditions for each and allows short-term exceptions approved by the responsible commanding officer [14]. Its long experience with BVLOS operations and its integration of military and civil certification principles make it a frequently cited reference model.

Germany offers perhaps the clearest example of deliberate convergence. Its Air Traffic Act exempts the armed forces from parts of ordinary aviation law, while explicitly noting that the EU civil UAS regulations do not bind the armed forces under Article 2(3) of Regulation (EU) 2018/1139 - yet its safety objectives must still be respected [15]. On this basis, the Luftfahrtamt der Bundeswehr (German Military Aviation Authority) defines nine UAS categories (I a-c, II LV/BV, II a-c, III a-b) built directly around the same parameters used in the civil Open category - aircraft mass, CE class marking, flight mode (VLOS/EVLOS/BVLOS) and overflowed ground area - while adding dedicated categories for collective/national-defence tasks and for larger, type-certified systems. Off-the-shelf UAS with an EU class marking (C0-C4) are automatically recognised for the corresponding military category without a separate type-approval procedure, which considerably shortens the introduction of new light systems.

The Netherlands has established a dedicated Military Aviation Authority that issues a self-standing body of military aviation regulations, including a recent specific regulation for unmanned aircraft systems (NLD-MAR-UAS) and related acceptable means of compliance, structured in a manner recognisably parallel to the civil EASA rulebook [16]. Together with wider European efforts to harmonise manned-aircraft military airworthiness codes [17], these examples show a consistent pattern: national military UAS regulation increasingly mirrors, without being legally bound by, the civil risk-based model, while retaining separate provisions for purely military tasks such as national and collective defence.

Table 1 summarises the resulting differences in legal basis, risk categorisation and airworthiness/training linkage between these three countries and the current Slovenian arrangement.

Country /model	Legal basis for state UAS	Risk-based categorisation	Airworthiness & training link
United Kingdom	Regulatory Article (RA) 1600 (military)	Defined operational categories with explicit conditions; short-term exceptions approved by the commanding officer	Converges with civil BVLOS and certification principles; long-standing operational experience
Germany	LuftVG § 30 (armed-forces exemption) + AR A1-270/4-8901 (LufABw)	Nine categories (I a-c, II LV/BV, II a-c, III a-b) mirroring the EU Open-category class marks, plus a dedicated national/collective-defence category	Automatic type recognition for CE class-marked UAS (C0-C4); STANAG-based certification for larger systems
Netherlands	Military Aviation Authority (MAA-NLD), NLD-MAR-UAS	Dedicated military aviation regulation for UAS, structured in parallel with the civil EASA rulebook	Acceptable means of compliance (AMC/GM) aligned with civil requirements
Slovenia (current state)	Dispersed: military aircraft regulation, UAS personnel licensing regulation, protection-and-rescue UAS regulation	Mainly aircraft mass and segregated-airspace reservations; limited risk-based differentiation	Airworthiness for UAS >150 kg largely borrows manned-aircraft criteria; no route for recognising NATO certificates

Table 1: Comparative overview of national regulatory approaches to state/military UAS.

COMPARISON WITH THE CURRENT STATE IN SLOVENIA AND PROPOSED GUIDELINES

Compared with these examples, Slovenian regulation of state UAS is fragmented across several instruments that were not designed as a coherent whole: separate rules govern military aircraft registration and airworthiness [18], military UAS personnel licensing [19], and UAS used for protection, rescue and disaster relief, the latter limited to 25 kg and only partly aligned with the EU product and operational categories [20]. A detailed regulatory gap-analysis of these instruments against EU legislation, NATO standards and foreign practice found, in summary, four recurring shortcomings: airspace-access rules rely mainly on aircraft characteristics and segregated-airspace reservations rather than on a genuine risk-based categorisation; BVLOS operations and detect-and-avoid requirements are only loosely defined; airworthiness provisions for UAS above 150 kg literally point to reasonably applied criteria for manned aircraft instead of UAS-specific standards; and there is no explicit mechanism for recognising foreign or NATO airworthiness certificates or crew qualifications [2].

As seen from the German, British and Dutch examples; none of these gaps require Slovenia to wait for EU or NATO legislation to change, because the necessary reference material - Regulations (EU) 2019/945 and 2019/947, SORA, STANAG 4670, 4671, 4702, 4703, 7234 and MUSRA - already exists and only needs to be consciously incorporated into national rules [2]. From this comparison we distil four guidelines for a future Slovenian regulatory act on state UAS operations. First, replace the current reliance on aircraft mass and segregated airspace with explicit, risk-based operational

categories, following the German practice of aligning the lowest categories directly with the EU class-marking system while reserving separate provisions for defence-specific tasks. Second, adopt SORA as the default risk-assessment methodology for civil-adjacent and specific operations, and MUSRA where military mission factors dominate, mirroring the UK's single coherent category structure. Third, base airworthiness requirements for UAS above the light-category threshold on STANAG 4671/4702/4703 rather than on manned-aircraft criteria, with a defined route for recognising NATO-issued certificates, as the Dutch and German authorities already do through structured military aviation regulations. Fourth, align crew training and licensing with STANAG 4670 and provide for mutual recognition of qualifications between NATO members, reducing the currently high entry requirements for instructors.

These four guidelines are deliberately structural rather than prescriptive: they do not require Slovenia to copy any single foreign model wholesale, but to choose, for each of the three regulatory domains, a reference point already validated abroad. For airspace integration, the German practice of tying the lightest categories directly to EU class marking while reserving a distinct category for national and collective-defence operations offers a low-cost starting point, since it requires no new technical infrastructure for the majority of currently used light UAS. For airworthiness, the Dutch model of a self-standing military aviation regulation structured in parallel with the civil rulebook shows that STANAG-based and EASA-based provisions can coexist without duplicating certification effort. For training, the United Kingdom's single set of operational categories, applicable across services, illustrates how competency-based qualification can replace the current split between civil-style and military-style instructor requirements. A single Slovenian regulatory act, rather than amendments scattered across the existing instruments, would make these choices visible and enforceable, and would give the Ministry of Defence, the Civil Aviation Agency and protection-and-rescue operators a common reference for future acquisitions and training programmes.

APPLICABILITY TO OTHER EU AND NATO MEMBER STATES

Although the comparison above centres on Slovenia, the underlying logic is not specific to any one country. Any EU and NATO member that has not yet formalised its state UAS regulation faces the same starting point: EU legislation excludes state operations from its scope while allowing a voluntary opt-in, and NATO standards apply only once nationally adopted. The transferable elements are, in our view, threefold. Risk-based operational categorisation can be defined regardless of a state's institutional structure, using SORA and MUSRA as ready-made assessment methodologies rather than developing new ones. Competency-based training aligned with STANAG 4670 supports mutual recognition of qualifications and therefore facilitates multinational exercises and operations, which is of particular value for smaller armed forces that routinely

operate alongside larger NATO partners. Finally, airworthiness standards such as STANAG 4671, 4702 and 4703 provide a common technical vocabulary that simplifies the acquisition of foreign-built systems and the recognition of certificates issued elsewhere in the alliance.

The framework outlined here should therefore be read as a regulatory model rather than a uniform legislative template. Its value lies less in the specific thresholds chosen by the United Kingdom, Germany or the Netherlands than in the shared decision to treat state UAS regulation as a conscious extension of, rather than an alternative to, the existing EU and NATO reference frameworks - a decision that remains open to any Member State, including Slovenia, regardless of the size of its armed forces or the density of its airspace.

CONCLUSIONS

Although EU aviation legislation does not bind Member States' state operations, and NATO standards are not directly applicable national law, both bodies of rules offer a mature, risk-based reference framework that individual states are free to adopt by choice. The examples of the United Kingdom, Germany and the Netherlands show that this is already common practice, typically implemented as a dedicated national military-aviation regulation that mirrors the civil risk categories while adding provisions specific to defence tasks. Slovenia currently lacks such a coherent framework: its rules for state UAS are dispersed across several instruments, rely mainly on aircraft mass and segregated airspace rather than on operational risk, and provide no route for recognising foreign airworthiness certificates or crew qualifications. Adopting EU regulatory principles together with the relevant NATO standards (STANAG 4670, 4671, 4702, 4703 and 7234) and risk-assessment methodologies (SORA and MUSRA) within a single national act would close these gaps, ease the integration of state UAS into Slovenian airspace, and align the country with the direction already taken by several of its EU and NATO partners.

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EFFECTS OF NORMOBARIC HYPOXIC EXPOSURE ON PHYSIOLOGICAL RESPONSES, COGNITIVE PERFORMANCE, AND SIMULATED FLIGHT PERFORMANCE IN GENERAL AVIATION PILOTS

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Abstract

Hypoxia is a major physiological hazard in aviation and can impair cognition, judgment, and flight performance even at altitudes relevant to general aviation. However, structured hypoxia training based on exposure is uncommon among general aviation pilots, and evidence linking physiological, cognitive, and simulator-based responses in this population remains limited.

This study examined the effects of controlled normobaric hypoxic exposure on physiological parameters, questionnaire-based cognitive performance, and simulated flight performance in general aviation pilots. Participants first completed baseline simulator tasks under normal conditions and then performed corresponding simulator tasks during hypoxic exposure in a normobaric altitude chamber. The simulator protocol included an ILS approach and an IMC maneuvering task. SpO₂ and heart rate were recorded at predefined phases of the chamber protocol, and questionnaire-based cognitive tasks were administered under baseline and hypoxic conditions.

Preliminary results indicated a clear and pronounced physiological response to hypoxic exposure with decreased SpO₂ and altered heart rate. Questionnaire-based cognitive task scores showed a consistent within-sample decrease under hypoxic exposure. Simulator-based analyses revealed heterogeneous effects on flight performance with changes in selected indicators of ILS tracking, maneuver execution and control behavior, and not a uniform deterioration across all variables.

The results support the use of a structured normobaric protocol as a useful framework for studying hypoxia-related performance changes and for improving aviation safety awareness in general aviation.

Keywords

hypoxia, normobaric hypoxia, altitude chamber, flight simulator, general aviation, pilot performance, aviation safety

INTRODUCTION

Hypoxia is a well-recognized physiological hazard in aviation, capable of impairing cognition, judgment, and psychomotor control before it is subjectively noticed [1]. In unpressurized flight, hypoxic hypoxia – the fall in inspired oxygen partial pressure with altitude – is the form most relevant to pilots.

This risk is particularly relevant to general aviation (GA), where it is often perceived as a high-altitude problem outside normal operating envelopes [2]. Experimental evidence at GA-relevant simulated altitudes has shown clear

physiological effects and increased procedural errors in more demanding phases of flight, particularly descent and approach [3], and survey-based evidence indicates that hypoxia-related events in GA are frequently underreported [4]. Unlike military aircrew, who typically undergo recurrent hypobaric or normobaric hypoxia refresher training, GA pilots rarely receive structured, exposure-based hypoxia training; awareness remains largely theoretical rather than grounded in direct, supervised experience of onset and symptoms [2].

This is a meaningful gap because hypoxia symptoms are insidious, non-specific, and individual, and self-recognition is often the only safety mechanism available to a single pilot in flight. Evidence also suggests that subjective symptom awareness can lag measurable physiological change [5], further undermining reliance on self-recognition alone. This points to a need for assessment approaches that combine controlled physiological exposure with realistic, simulator-based flight tasks, so that the association between hypoxic state and performance can be observed rather than only described. Physiological, questionnaire-based, and simulator-derived measures each capture a different, partial aspect of this response, and combining them within a single within-subject protocol may give a more complete picture than any one domain alone.

The aim of the present study was to examine, within a within-subject comparison of normal atmospheric conditions and controlled normobaric hypoxic exposure, changes in physiological responses, questionnaire-based cognitive performance, and simulator-derived flight performance metrics in participants with an aviation background.

THEORETICAL FRAMEWORK

Basic aviation hypoxia physiology

Hypoxic hypoxia results from the decrease in atmospheric pressure and inspired oxygen partial pressure with increasing altitude, and is distinguished from hypemic, stagnant, and histotoxic hypoxia [1, 6]. Reductions in ambient pressure at GA-relevant altitudes are sufficient to measurably lower arterial oxygen saturation (SpO₂) in most individuals, with a compensatory rise in heart rate [1]. Time of useful consciousness (TUC), the period during which effective action remains possible after significant hypoxia onset, is reported to fall sharply with altitude under rapid-onset conditions [7]. These figures illustrate the altitude-

dependent severity of hypoxic exposure only, and are not directly comparable to the gradual, controlled normobaric exposure used here.

General aviation and mild hypoxia

Nesthus et al. [3] compared ten GA pilots breathing simulated-altitude oxygen mixtures (8,000–12,500 ft equiv.) against ten pilots breathing normal air, across a multi-day cross-country simulator scenario. Physiological measures (SaO₂, tissue PO₂, heart rate) differed clearly and consistently between groups by altitude. Basic flight-parameter accuracy during level cruise (altitude, heading, and VOR tracking error) did not differ significantly. However, the hypoxia group committed significantly more procedural errors than controls, concentrated in descent and approach phases, and reported significantly higher perceived temporal workload; subjective symptom questionnaires otherwise showed only limited group differentiation. This pattern – clear physiological change, largely unaffected basic flight parameters, and selective performance effects concentrated in more demanding flight phases – closely parallels the multi-domain distinction adopted in the present study. Separately, survey-based evidence indicates that hypoxia-related events in GA are frequently underreported, reinforcing the practical training gap rather than adding further performance evidence [4].

Normobaric versus hypobaric hypoxia

Hypoxic conditions can be induced by physically reducing chamber pressure (hypobaric hypoxia) or by reducing the fraction of inspired oxygen at ambient pressure (normobaric hypoxia). A systematic review of crossover trials found the two are not physiologically identical, with hypobaric exposure additionally involving reduced total barometric pressure [8]. Normobaric systems are more logistically accessible for repeated non-medical use, which motivated their use here, but the distinction remains a methodological limitation when generalizing to true-altitude (hypobaric) exposure.

Cognitive effects and symptom delay

In a controlled normobaric hypoxia exposure study using healthy participants and an aviation survival trainer paradigm (not a pilot-specific flight-performance study), physiological change – SpO₂ decline and heart-rate increase – occurred within 2–3 minutes of onset, while subjective symptom reporting was delayed by several minutes; more complex cognitive tasks (e.g., working memory, inhibitory control) appeared more sensitive to hypoxic impairment than simpler measures [5]. This dissociation between rapid physiological response and delayed subjective awareness motivates the inclusion of a questionnaire-based cognitive component alongside physiological monitoring in the present protocol.

Simulator-based flight performance under normobaric hypoxia

In Finnish Air Force fighter pilots tested in a tactical Hawk flight simulator, normobaric hypoxia exposure was associated with a dose-dependent decrease in Instrument Landing System (ILS) approach performance, with effects persisting after hypoxia emergency procedures and oxygen recovery – described as a “hypoxia hangover” [9, 10]. Effects were not uniform across all flight parameters and varied with exposure severity and individual response. As a military fast-jet population, this literature is not directly generalizable to GA, but it supports treating simulator-derived flight performance effects of hypoxia as task-dependent and heterogeneous rather than uniform, and informs the inclusion of both a structured ILS approach task and a separate IMC maneuvering task in the present protocol.

Transition to the present study

Taken together, this literature indicates that hypoxic hypoxia is a credible risk at GA-relevant altitudes, that physiological and subjective/cognitive responses to mild hypoxia do not necessarily track each other in time, and that simulator-derived flight performance effects reported elsewhere are task-dependent rather than uniform. Direct, within-subject evidence combining physiological, cognitive, and simulator-derived flight performance measures in a GA-relevant population remains scarce. A prior diploma thesis provided the conceptual and methodological basis for simulator-based hypoxia recognition training [11]; the present paper reports a separate, subsequent experimental implementation using normobaric hypoxic exposure, detailed in the Methods section.

METHODS

Study design

This study used an exploratory, within-subject (repeated-measures) design to compare physiological responses, questionnaire-based cognitive performance, and simulator-derived flight performance between two conditions: baseline (normal atmospheric conditions) and normobaric hypoxic exposure.

The primary analysis compared baseline performance under normal atmospheric conditions with the selected, complete hypoxic exposure session. For readability, this condition is referred to as “hypoxia” throughout the manuscript.

Condition order was fixed: the baseline session was always conducted before the hypoxic session, for logistical reasons related to chamber scheduling. The comparison was therefore not randomized, and possible order effects cannot be fully separated from hypoxia effects; this is addressed as a limitation.

The experimental protocol was implemented within a structured training framework, which provided the organizational and safety context for data collection. The

manuscript focuses on the research protocol, measured variables, and findings rather than on the educational program itself.

Participants and data inclusion

Participants were individuals with an aviation background, including licensed pilots and pilot trainees with prior theoretical aviation training and some flight experience. Detailed demographic characteristics and flight-experience variables, such as age, sex, license status, and total flight hours, were not systematically collected and are therefore not reported.

Participants voluntarily enrolled in the structured training program. Before participation, they were informed about the experimental procedures and safety measures and provided informed consent to participate. No formal demographic research dataset was collected beyond the measurements required for the training and experimental protocol.

Only complete baseline–hypoxia pairs were included in each paired analysis. Consequently, the number of valid paired observations differed across data streams: physiological and questionnaire-based analyses included eight participants, the ILS simulator analysis included seven participants, and the IMC maneuvering task analysis included eight participants.

The reduced sample for the ILS analysis ($N = 7$) reflects one participant for whom no baseline ILS recording was available. Although the participant completed the ILS task under the hypoxic condition, the absence of the corresponding baseline recording prevented inclusion in the paired ILS analysis.

Experimental protocol

The training and data-collection program comprised three components: a theoretical module on the physiology of hypoxia, hypoxic symptoms, and time of useful consciousness (TUC), together with safety briefings; a baseline simulator session under normal atmospheric conditions, consisting of the ILS approach task and the structured IMC maneuvering task; and a normobaric altitude chamber session in which corresponding ILS and IMC tasks were performed under hypoxic exposure. During the chamber session, physiological measurements were recorded at predefined protocol phases. Self-reported symptoms were collected as supporting observations.

Prior to chamber exposure, participants received theoretical instruction and safety briefings delivered by aviation and medical experts, including pilots with military hypoxia training experience and physicians with expertise relevant to aviation physiology and hypoxia.

Participants completed the questionnaire-based cognitive task under baseline conditions and again during the selected hypoxic session.

Normobaric altitude chamber exposure

Normobaric hypoxic exposure was conducted in a normobaric altitude chamber at the Jožef Stefan Institute (IJS), Ljubljana.

The chamber reduces the fractional concentration of oxygen at ambient barometric pressure to produce a physiologically equivalent altitude, rather than reducing barometric pressure directly as in a hypobaric chamber; this distinction between normobaric and hypobaric hypoxia is addressed as a limitation.

The simulated equivalent altitude was approximately 5,000–6,000 m (~16,400–19,700 ft). Individual in-chamber exposure duration was approximately 30 minutes. Participants received safety instructions before entering the chamber, and medical personnel were present during the experimental exposure. Exposure was conducted under medical supervision, with supplemental oxygen available for immediate reoxygenation. A predefined safety stop criterion ($SpO_2 < 70\%$) applied throughout.

Simulator setup

Flight tasks were performed in Microsoft Flight Simulator 2020 using a Cessna 172 with conventional analogue instrumentation and Honeycomb Aeronautical flight controls. The same simulator configuration was used for baseline and hypoxic recordings.

All tasks were flown at the simulated Ljubljana Jože Pučnik Airport (ICAO: LJLJ). Flight parameters were logged using Flight Recorder software at 85 Hz and exported as CSV files for offline analysis.

Flight tasks

ILS approach task

The ILS task consisted of an instrument approach to runway 30 at Ljubljana Jože Pučnik Airport (LJLJ). The aircraft was initially positioned 15 NM from the runway threshold at 4,000 ft. The first part of the task consisted of level flight prior to glide-slope interception, followed by descent on the ILS glide path after the glide-slope intercept at approximately 8.9 NM.

Altitude-related metrics, including altitude variability and deviation from the assigned 4,000 ft level segment where applicable, were computed for the level portion prior to glide-slope interception. Glide-slope error metrics were computed for the descent segment after glide-slope interception.

The task was flown under simulated instrument meteorological conditions (IMC), requiring the participant to track the localizer and glide slope using instruments alone.

Structured IMC maneuvering task

The second simulator task was a structured IMC maneuvering task consisting of straight-flight segments, prescribed heading changes, standard-rate turns, and altitude-change maneuvers. This task was used to assess maneuver execution, turn-rate control, altitude-change accuracy, straight-segment stability, and control activity.

The implemented baseline version of the IMC task contained seven planned turns, whereas the implemented hypoxic version contained five planned turns. Therefore, total task duration, total turn count, and total maneuver geometry were treated as protocol characteristics rather than primary indicators of hypoxia-related performance change.

Physiological measurements

SpO₂, chamber oxygen concentration, and heart rate were recorded at predefined protocol phases: chamber entry, after the ILS task, after the IMC maneuvering task, and after the questionnaire/cognitive test.

Questionnaire/cognitive measures

A questionnaire-based cognitive task was administered, comprising mental arithmetic performed without aids, number-series and logic tasks, a maze task, and top-of-descent/rate-of-descent calculation tasks. For the main analysis, performance was summarized using the total questionnaire-based score expressed as a percentage.

For the main analysis, the total questionnaire-based cognitive test score under baseline conditions was compared with the corresponding score from the selected hypoxic session. The paired difference was computed as hypoxia minus baseline.

Simulator-derived performance measures

ILS approach measures

Localizer tracking accuracy was assessed using the mean absolute localizer deviation, the root-mean-square localizer deviation, the 95th-percentile absolute localizer deviation, and the maximum absolute localizer deviation. Localizer deviation was expressed in degrees. Larger values represented greater lateral deviation from the localizer reference.

Glide-slope tracking accuracy, assessed for the descent segment after glide-slope interception, used the mean absolute vertical deviation from the reference glide path, the root-mean-square glide-slope error, the 95th-percentile absolute glide-slope error, and the maximum absolute glide-slope error. Glide-slope error was expressed in feet. Larger values represented greater vertical deviation from the reference glide path.

Flight-path stability was assessed using the standard deviation of indicated airspeed, the standard deviation of pitch attitude, the standard deviation of altitude during the level-flight segment before glide-slope interception, the standard deviation of bank angle, and the circular standard deviation of heading. Larger values represented greater variability in the corresponding flight parameter.

Control activity was assessed using the root-mean-square rate of elevator and aileron movement, and the frequency of elevator and aileron corrections per minute. These measures represented the magnitude and frequency of control-input activity. Greater control activity must not automatically be interpreted as poorer performance, because it may also represent compensatory control behavior.

Structured IMC maneuvering measures

Straight-segment stability, assessed during non-turning task segments, used the variability of indicated airspeed, the variability of altitude, and the circular variability of heading. These measures were treated as descriptive indicators of overall variability during non-turning segments rather than as direct target-tracking errors, because individual straight segments had different assigned headings and altitude states.

Turn execution was assessed using the mean variability of bank angle during turns, and the mean and root-mean-

square deviation from the standard-rate-turn reference. The reference turn rate was 3 degrees per second. Turn-rate error was expressed in degrees per second. Larger errors represented greater deviation from the standard-rate reference.

Maneuver accuracy, reflecting the accuracy of the instructed maneuver sequence, was assessed using the mean absolute error between instructed and executed turn angle, the mean absolute error between instructed and executed altitude change, and the mean turn-rate error for the instructed maneuver sequence. Turn-angle error was expressed in degrees, altitude-change error in feet, and turn-rate error in degrees per second. Larger values represented lower maneuver accuracy.

Control activity during the IMC task was assessed using the root-mean-square rate of elevator and aileron movement, and the elevator and aileron correction frequency per minute. These measures described control-input magnitude and correction frequency. Greater activity must be interpreted in the context of the task and must not automatically be treated as degraded performance.

Protocol-dependent measures excluded from primary interpretation

The implemented baseline IMC task contained seven planned turns, whereas the implemented hypoxic task contained five planned turns. Accordingly, total task duration, total turn count, and total maneuver geometry were treated as protocol characteristics rather than primary indicators of hypoxia-related performance change. Primary comparisons focused on per-segment, per-turn, and per-maneuver measures wherever possible.

Statistical and analytical approach

Paired descriptive statistics, paired differences, percentage changes, standardized changes, and exploratory paired statistical tests were computed. Because of the small sample size and the large number of derived measures, the results are interpreted primarily descriptively and exploratorily rather than as confirmatory evidence.

For each measure, the following were computed: mean $\pm$ sample SD by condition; paired difference, defined as hypoxia minus baseline; percentage change; and baseline-standardized change, calculated as the mean paired difference divided by the baseline sample SD. Cohen's d_z , calculated as the mean paired difference divided by the sample standard deviation of the paired differences, was used as the principal standardized paired-change measure [12]. Paired t-tests and Wilcoxon signed-rank tests [13] were performed as exploratory supporting analyses where relevant.

Because the study was exploratory and involved multiple derived measures, p-values, where reported, were treated as descriptive/supporting information rather than confirmatory evidence. Statistical significance is not treated as the primary evidence for an effect unless explicitly addressed in the Results.

For all measures, a positive change (hypoxia – baseline) does not uniformly indicate degraded performance; interpretation is measure-specific. For most error, variability, and control-activity measures, higher values indicate greater deviation, variability, or control activity. For physiological variables, a decrease in SpO₂ is the expected direction of the hypoxic response, and an increase in heart rate may reflect a compensatory physiological response.

Data processing was performed in Python using custom analysis scripts. The scripts converted raw simulator data into task-specific measures, generated quality-control plots, computed paired baseline–hypoxia differences, and created summary figures for visual inspection of individual and group-level patterns.

RESULTS

Physiological response

Physiological measures were recorded at four phases of the hypoxic exposure session – chamber entry, after the ILS task, after the IMC maneuvering task, and after the questionnaire/cognitive test – for all $N = 8$ participants. Chamber O₂ concentration was reduced and stable throughout exposure (approximately 10%), confirming a sustained hypoxic gas environment. At chamber entry, SpO₂ was still close to normal ($98.1 \pm 0.4\%$), reflecting the brief physiological lag before oxyhemoglobin saturation responds to reduced ambient O₂. SpO₂ then decreased markedly across subsequent phases, while heart rate increased relative to entry at every later phase (Table 1).

Phase	SpO ₂ (%)	Heart rate (bpm)	Chamber O ₂ (%)
Chamber entry	98.1 ± 0.4	79.4 ± 9.6	10.2 ± 0.4
After ILS task	80.6 ± 6.7	94.3 ± 12.0	10.3 ± 0.3
After IMC task	76.9 ± 7.1	98.0 ± 11.9	10.2 ± 0.3
After questionnaire	76.9 ± 5.0	90.6 ± 16.7	10.3 ± 0.2

Table 1: Physiological measures by protocol phase ($N = 8$, mean $\pm$ sample SD).

Standardized paired changes from entry were large for both SpO₂ (d_z ranging from -2.60 to -4.13 across phases) and heart rate (d_z ranging from 1.31 to 3.35), indicating a consistent and pronounced physiological response to exposure.

Physiological response during hypoxic exposure

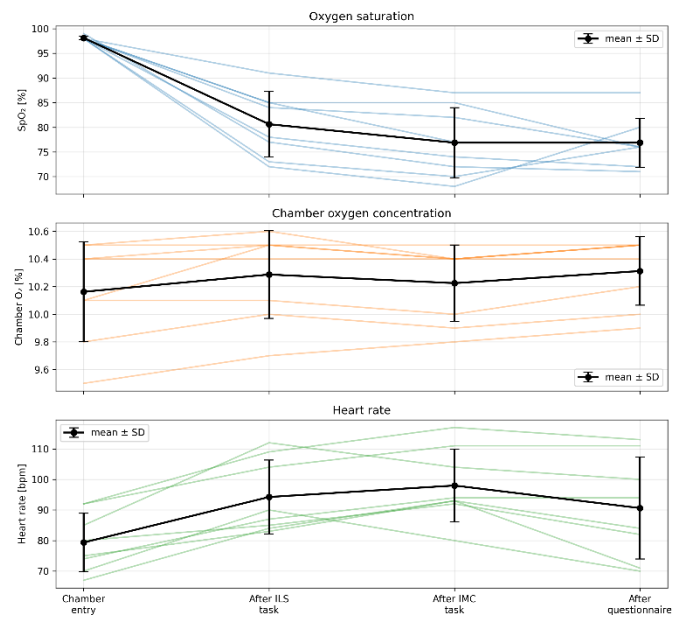


Figure 1: Physiological response across predefined phases of normobaric hypoxic exposure. Thin lines represent individual participants; the black line and error bars represent mean $\pm$ sample SD.

Questionnaire-based cognitive task performance

Questionnaire-based total scores decreased from the baseline condition to the hypoxic condition for all $N = 8$ participants (baseline: $96.3 \pm 5.2\%$; hypoxia: $81.9 \pm 10.7\%$; mean paired change: -14.4 ± 9.4 percentage points, approximately -15.0% ; Cohen's $d_z = -1.53$). Exploratory paired testing supported this pattern, but given the sample size and exploratory design, the result is interpreted descriptively rather than as confirmatory evidence of a cognitive impairment effect.

Questionnaire-based cognitive task performance

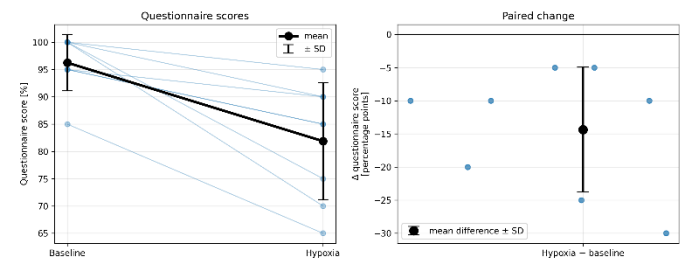


Figure 2: Questionnaire-based cognitive task performance under baseline and hypoxic conditions. Individual paired observations and the group mean $\pm$ sample SD are shown together with the paired change.

ILS simulator performance

Localizer- and glide-slope-deviation measures are expressed in degrees and feet, respectively. Localizer tracking showed small, directionally mixed changes under the hypoxic condition, with the mean absolute deviation numerically lower but peak-deviation measures essentially

unchanged. Glide-slope error measures were numerically lower under the hypoxic condition; however, given the fixed order of conditions, small sample size, and high inter-individual variability, this should not be interpreted as evidence of improved glide-slope performance under hypoxia. Flight-path stability measures (airspeed, pitch, altitude, bank, and heading variability) and control-activity measures (elevator and aileron control rate and correction frequency) each showed only small changes in both directions. p-values are reported descriptively and should not be interpreted as confirmatory because of the exploratory design and the number of derived measures examined. Detailed per-measure results were retained in the analysis dataset.

IMC maneuvering task performance

The baseline IMC task contained seven planned turns, while the hypoxic-condition IMC task contained five; total duration, turn count, and overall maneuver geometry therefore reflect this protocol difference and are not interpreted as hypoxia-related performance effects. Straight-segment variability measures showed small numerical increases under the hypoxic condition and were treated as descriptive indicators of overall non-turning segment variability rather than direct target-tracking errors, since the task contained multiple straight segments with different expected headings and altitude states. Turn-execution measures relative to the standard-rate-turn reference showed small-to-moderate decreases. Expected-vs-actual maneuver accuracy showed a numerical increase under the hypoxic condition in both angular and altitude-change error, described as an observed pattern with high variability: one isolated direction-mismatch event increased between-participant variability and should not be interpreted as a group-level pattern. Control-activity measures showed small increases under the hypoxic condition. No IMC measure reached conventional statistical significance; p-values are reported descriptively only. Detailed per-measure results were retained in the analysis dataset.

Summary of standardized changes

Standardized paired changes (Cohen's d_z) were consistently larger for physiological and questionnaire-based measures than for simulator-derived flight performance measures, where the largest standardized changes observed were of moderate magnitude. This pattern is consistent with the overall preliminary characterization of the study: normobaric hypoxic exposure produced a clear and pronounced physiological and questionnaire-based response, while simulator-derived flight performance changes were smaller, heterogeneous across measures and task domains, and did not reach conventional statistical significance in this sample.

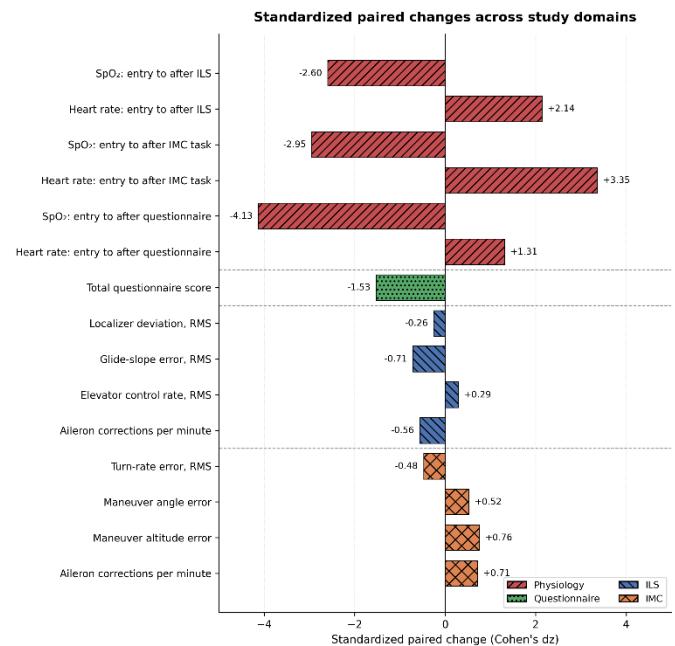


Figure 3: Standardized paired changes across physiological, questionnaire-based, and simulator-derived domains. Values are expressed as Cohen's d_z ; positive and negative values indicate the direction of change from baseline to the hypoxic condition and do not uniformly represent improvement or deterioration.

DISCUSSION

Principal's findings

This exploratory within-subject study examined the effects of controlled normobaric hypoxic exposure on physiological responses, questionnaire-based cognitive task performance, and simulator-derived flight performance in a small sample of participants with an aviation background, including licensed pilots and pilot trainees. Three broadly separable response patterns emerged. First, hypoxic exposure produced a clear and physiologically expected response, characterized by a marked decrease in SpO₂ and an increase in heart rate relative to chamber entry, consistent with stable chamber oxygen concentration near 10%. Second, questionnaire-based cognitive task performance decreased consistently across all participants, with a paired change and effect size suggesting a substantial within-sample shift. Third, simulator-derived flight performance measures – across both the ILS approach task and the IMC maneuvering task – showed small-to-moderate and directionally mixed changes, with no individual simulator-derived measure reaching conventional statistical significance. Taken together, these findings support the framing that physiological and questionnaire-based effects were more pronounced and consistent than simulator-derived effects, which appeared selective and task-dependent rather than uniformly degraded.

Physiological and questionnaire-based responses

The observed decline in SpO₂ alongside a compensatory increase in heart rate is consistent with the expected physiological response to acute hypoxic exposure and aligns with prior findings on aviation-relevant normobaric hypoxia [1, 3]. The direction of the physiological response was consistent across participants, despite known inter-individual variability in hypoxia tolerance and response magnitude [1], suggesting that the exposure protocol reliably induced a measurable physiological hypoxic state within the tested duration and altitude equivalent.

The decrease in questionnaire-based cognitive task performance observed in all eight participants, with a paired change and Cohen's d_z indicating a large within-sample effect, is broadly consistent with reports that cognitive performance – particularly on tasks involving more complex processing – may be sensitive to hypoxic exposure even in healthy, physiologically resilient individuals [5]. This pattern is also consistent with the broader observation that physiological changes may precede or accompany measurable cognitive change before subjective symptom recognition occurs [5], a mechanism of direct relevance to hypoxia recognition training in aviation contexts. However, this result should be interpreted cautiously: the questionnaire was task-specific rather than a validated clinical or psychometric instrument, the sample was small, and the fixed baseline-then-hypoxia session order means that learning, fatigue, or repeated-task effects cannot be fully separated from hypoxia-specific effects. The magnitude of the effect size should therefore be read as a preliminary indicator of a within-subject pattern rather than as a precise or generalizable estimate.

ILS and IMC simulator-derived performance

In contrast to the physiological and questionnaire domains, simulator-derived flight performance measures did not show a consistent or uniform pattern of degradation. For the ILS approach task, localizer tracking, glide-slope tracking, flight-path stability, and control-activity measures showed small-to-moderate changes without a consistent direction, and no measure reached conventional statistical significance. Notably, glide-slope error was numerically lower under hypoxic exposure for some measures; this should not be interpreted as evidence of improved performance under hypoxia, but rather considered alongside plausible alternative explanations, including the fixed condition order, task familiarization or procedural learning between sessions, compensatory effort or increased attentional prioritization of a well-practiced precision task, and inherent inter-individual variability in a small sample.

For the IMC maneuvering task, straight-segment stability, turn-execution accuracy, maneuver accuracy, and control-activity measures showed heterogeneous changes. Angular and altitude-change errors increased numerically under hypoxic exposure, but with considerable between-participant variability, partly influenced by an isolated direction-mismatch event in one participant. Control activity

showed only small numerical increases. Differences in total task duration, turn count, or overall maneuver geometry between conditions must not be interpreted as hypoxia-related effects, as the baseline and hypoxic IMC protocols differed in the number of planned turns (seven versus five); this is a protocol-level limitation rather than a performance outcome.

These simulator-derived patterns are broadly consistent with earlier findings that basic flight parameters may remain relatively preserved under acute hypoxic exposure, while procedural or task-specific errors emerge more readily during demanding flight phases [3]. Comparisons with military simulator studies examining hypoxia and ILS performance [9, 10] are offered here only as contextual reference points; the present study did not replicate the Varis protocol, and the participant population – aviation-background individuals rather than licensed military fighter pilots – differs meaningfully in training, procedural automaticity, and prior hypoxia exposure history. Direct generalization between these populations is therefore not warranted.

Task dependency, compensation, and individual variability

The dissociation between clear physiological change and questionnaire-based cognitive task performance change, on one hand, and heterogeneous simulator-derived change, on the other, may partly reflect differences in task demand, automaticity, and the ability of participants to allocate compensatory effort to well-structured, procedurally supported flight tasks. Participants may have maintained selected flight parameters through increased effort, prioritization of critical instruments, or reliance on over-learned procedural skill, even as physiological state and questionnaire-based cognitive task performance were measurably reduced. Although compensatory effort and attentional prioritization offer plausible explanations, workload and strategy use were not measured directly in the present study. This interpretation is consistent with observations that basic flight control may be relatively protected relative to higher-order or less-practiced task components under hypoxic stress [3].

The absence of statistically significant simulator-derived effects should not be interpreted as evidence of no effect; the study was not powered to detect small-to-moderate effects at the individual-measure level. The large number of derived measures and the absence of correction for multiple comparisons increased the risk of false-positive findings, while the small sample size and limited statistical power increased the possibility of false-negative findings. It also remains possible that some cognitive or perceptual effects may persist beyond the end of hypoxic exposure or recover more slowly than peripheral oxygenation, as suggested by evidence of delayed recovery of selected cognitive and perceptual functions following normobaric hypoxic exposure [14]. The present protocol, which assessed performance during a single, time-limited exposure phase, may not have fully captured such persisting or slowly recovering effects. Additionally, the physiological differences between normobaric and hypobaric hypoxia [8]

limit the extent to which findings from this normobaric protocol can be generalized to hypobaric altitude exposure, a distinction relevant to interpreting comparisons with hypobaric or high-altitude aviation literature.

Implications for aviation safety and hypoxia recognition training

The overall pattern observed – a clear physiological response and a clear decrease in questionnaire-based cognitive task performance occurring alongside relatively preserved but selectively affected simulator flight performance – has potential relevance for aviation safety and hypoxia recognition training. The observed pattern suggests that relatively preserved performance in selected simulator measures should not be assumed to indicate the absence of physiological or questionnaire-based effects. This reinforces the value of structured recognition training that relies on physiological and symptom awareness rather than on self-assessment of flight performance. These preliminary findings are consistent with the broader rationale for practical, protocol-based hypoxia recognition training in general aviation, where such training remains limited relative to structured exposure-based hypoxia-recognition practices used in military aviation. Given the exploratory nature and small sample size of the present study, these implications should be regarded as hypothesis-generating rather than confirmatory, and are intended to motivate further, adequately powered research rather than to establish definitive training recommendations.

Limitations

Several limitations should be considered when interpreting these preliminary findings. The sample size was small and varied by analysis domain ($N = 8$ for physiological and questionnaire measures, $N = 7$ for ILS performance, $N = 8$ for IMC performance), limiting statistical power and the precision of effect-size estimates. Participants had mixed aviation backgrounds and were not exclusively licensed general aviation pilots; detailed demographic and flight-experience variables were not systematically collected, limiting characterization of the sample and constraining comparisons with populations examined in prior studies.

The experimental protocol used a fixed order of baseline followed by hypoxic exposure, without randomization or counterbalancing. This design cannot fully exclude learning, familiarization, fatigue, or expectancy effects as contributors to the observed within-subject changes, particularly for the questionnaire-based and ILS performance results. Physiological measurements were recorded at discrete phases rather than continuously throughout exposure, which may limit sensitivity to transient physiological changes. Normobaric hypoxic exposure is not physiologically identical to hypobaric altitude exposure, and findings from this protocol should not be directly generalized to hypobaric conditions encountered in actual high-altitude flight.

The baseline and hypoxic IMC maneuvering protocols differed in the number of planned turns (seven versus five), representing a protocol-level asymmetry that constrains

direct comparison of task duration, turn count, and overall maneuver geometry between conditions. The large number of derived simulator measures examined across the ILS and IMC tasks, combined with the absence of correction for multiple comparisons, increased the risk of false-positive findings, while the small sample size and limited statistical power increased the possibility of false-negative findings. The questionnaire used to assess cognitive task performance was task-specific and had not been validated as a clinical or standardized psychometric instrument. Finally, simulator-based performance, while informative for controlled experimental comparison, is not a direct substitute for real-flight performance, and findings should be interpreted within the context of a simulated, low-stakes task environment.

CONCLUSIONS

Controlled normobaric hypoxic exposure produced a clear physiological response in participants with an aviation background, consistent with expected changes in oxygen saturation and heart rate during exposure. Questionnaire-based cognitive task performance decreased consistently within the sample, showing a measurable within-sample change associated with the hypoxic condition. In contrast, simulator-derived flight performance measures for both the ILS approach task and the IMC maneuvering task showed smaller, heterogeneous, and task-dependent changes across participants. Given the limited sample size and exploratory statistical approach, the absence of uniform or conventionally significant changes in simulator-derived measures should not be interpreted as evidence that hypoxic exposure had no effect on flight performance.

These preliminary findings support the feasibility of combining physiological monitoring, questionnaire-based cognitive assessment, and simulator-derived performance measures within a single normobaric hypoxia protocol for exploratory research in general aviation contexts. The approach may hold relevance for aviation-safety awareness and hypoxia-recognition training. However, the results are preliminary and derived from a small volunteer sample and a fixed, non-randomized condition order; confirmation in larger, better-characterized studies employing randomized or counterbalanced designs is required before drawing firm conclusions about the effects of hypoxia on simulated flight performance.

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DESIGN AND MANUFACTURE OF THE REMOTE-CONTROLLED AIRCRAFT BRVINC FOR THE DESIGN/BUILD/FLY 2026 COMPETITION

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Abstract

Design/Build/Fly is an annual aerospace design competition organised by the American Institute of Aeronautics and Astronautics. Its main goal is to give students the opportunity to apply their theoretical knowledge to design and manufacture a remote-controlled (RC) aircraft for a specific set of missions. Student teams engage in problem-solving, research, development, testing, and ultimately the flight demonstration of their aircraft at the competition. This paper describes the aircraft Brvinc, designed and manufactured by the Edvard Rusjan Team from the University of Ljubljana. First, a brief overview of the DBF 2026 rules and regulations is provided, with this year's focus on efficient passenger and cargo transport as well as banner towing. Our approach to the preliminary design of the aircraft, manufacturing process, flight testing and validation is detailed next. Finally, the paper summarizes the team's outstanding performance at the fly-off, where it secured first place.

Keywords

Design/Build/Fly competition, radio-controlled aircraft, aircraft design, mission analysis, banner towing, flight testing

INTRODUCTION

The Edvard Rusjan Team from the University of Ljubljana designed, manufactured and tested the radio-controlled aircraft Brvinc for the 2026 American Institute of Aeronautics and Astronautics (AIAA) Design/Build/Fly (DBF) competition [1]. The competition requires student teams to design an aircraft that meets a set of annual mission requirements, build it, and demonstrate its performance during a fly-off. The project therefore combines aircraft design and manufacturing with testing, flight operations and teamwork [2]. Brvinc is shown during the banner-towing mission in Figure 1.

The 2026 competition challenged teams to design a banner-towing bush plane capable of performing charter flights with passengers and cargo, as well as deploying and towing a banner. It included three flight missions and a timed ground mission [2]. The fly-off took place in Wichita, Kansas, USA, from 16 to 19 April 2026 [3].

Mission 1 was a test flight without payload, requiring three laps. Mission 2 required the aircraft to carry passengers and cargo, represented by standard rubber ducks and hockey pucks, respectively, and complete as many laps as possible within a five-minute window. Its score was based on the payload carried, the number of laps completed and the propulsion battery capacity. Mission 3 required teams to deploy and tow a banner in flight, completing as many laps

as possible within a five-minute window. Its score depended on the number of laps completed, the banner's length and the aircraft's rated aircraft cost (RAC), based on the aircraft's wingspan. The banner's length-to-height ratio could not exceed 5:1. The ground mission tested the team's ability to quickly load and unload passengers and cargo, install the banner, and demonstrate its deployment and release. The goal was to complete the sequence in the shortest possible time [2]. The University of Ljubljana won the competition, which was attended by 89 university teams [3].



Figure 1: Brvinc during the 2026 DBF fly-off in Wichita, Kansas, USA.

Brvinc was developed by 48 students supervised by a faculty advisor. The team was divided into seven sub-teams: Simulations and Testing, Aerodynamics, CAD, CAM, Manufacturing, Electronics, and Finances and Public Relations. The aircraft and its mission equipment were designed together, with particular attention to stability while towing a banner, quick access to payload compartments and rapid aircraft reconfiguration during the ground mission.[1]

AIRCRAFT DESIGN

Design approach and mission trade-offs

The competition requirements were converted into general aircraft, mission and subsystem requirements. These included the maximum wingspan, propulsion and battery limits, payload capacity, restraint systems, and the time available for aircraft configuration. The aircraft also had to pass a wingtip load test and remain airworthy after each flight [2].

Several aircraft configurations were compared using weighted decision matrices. The conventional configuration achieved the highest score among the conventional, tandem, and flying-wing concepts. It provided good stability and control, flexible payload integration and a layout that could be manufactured using the team's existing experience. A low-wing arrangement was selected after payload access, banner access, stability and manufacturability were considered. The conventional tail was preferred to T-tail and V-tail alternatives because it offered a straightforward structure and predictable control. Tricycle landing gear was selected because it provided good banner access while retaining simple construction and ground handling.[1]

Mission-score simulations showed that the flight missions and the ground mission favoured different payload configurations. Figure 2 presents the normalized total mission score as a function of passenger and cargo count. Two distinct high-scoring regions can be identified: one at low payload counts, where shorter handling time benefits the ground mission, and another at moderate payload counts, where the Mission 2 score is higher. Because the flight missions involved greater uncertainty and a wider range of potential failure modes than the ground mission, the team selected the GM-oriented strategy. This decision accepted a lower potential Mission 2 score in exchange for shorter handling time and more repeatable ground-mission execution. It also allowed the design to focus on Mission 3 performance and resulted in a more compact aircraft, simplifying the manufacturing process.[1]

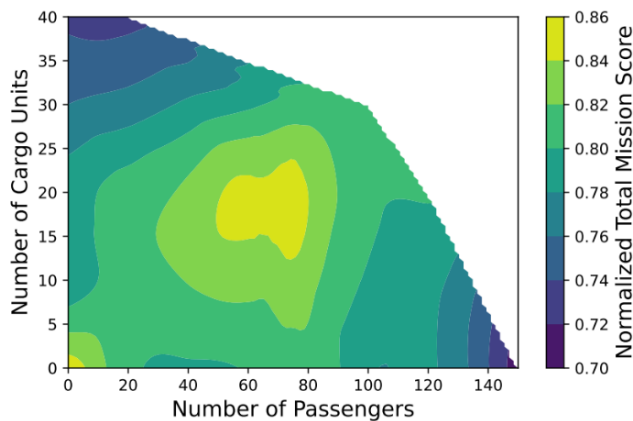


Figure 2: Normalized total mission score as a function of passenger and cargo count [1].

Banner length was a key design variable for Mission 3. Figure 3 shows how the primary score factor, calculated as the product of the number of completed laps and banner length, varied with banner length for different banner drag coefficients. Increasing banner length initially increased the score factor. However, the additional drag eventually reduced the number of laps that could be completed within the five-minute window, causing a sharp drop in the score factor. This produced a sawtooth trend, with local optima just below the banner lengths at which a lap was lost. Lower banner drag allowed longer banners to be flown before reaching these thresholds.[1]

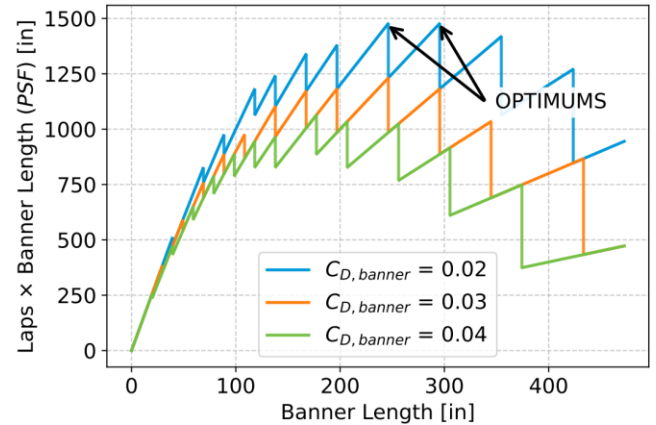


Figure 3: Primary score factor (PSF) versus banner length for different banner drag coefficients [1].

Preliminary design and aerodynamic analysis

A custom aircraft mission simulation written in Python was used to evaluate combinations of motor, propeller, battery, wingspan, wing chord, payload count and banner length. The model represented straight and turning segments of the flight course and included the effect of wind on ground speed. It estimated lap count, lap time, energy consumption and mission score, providing a basis for comparing candidate configurations.

Different airfoils were assessed at Reynolds numbers corresponding to the expected flight speeds. Airfoil data were obtained from the Airfoil Tools database [4] and analysed in XFLR5 [5]. Lift, drag, pitching moment and stall behaviour were considered. The NACA 4412 airfoil was selected for the main wing because it provided suitable lift at low speeds and a gradual stall characteristic. Symmetrical NACA 0012 airfoils were selected for the horizontal and vertical stabilizers.

Five wing planforms were compared using aerodynamic and structural criteria. An asymmetrically tapered planform was selected as a compromise between aerodynamic performance and structural simplicity. Its geometry allowed the use of a straight main spar, simplifying the wing structure and manufacturing process.

Wing sizing involved a trade-off between the flight missions. Mission 2 generally favoured greater wing area to support higher payload capacity, whereas the Mission 3 score favoured shorter wingspans because of the RAC penalty. However, the wing-sizing study showed that the penalty reduced the score by only approximately 4% across the investigated range. As shown in Figure 4, the normalized Mission 3 score varied only slightly with wingspan. The team therefore accepted this reduction and selected a wingspan of 1.50 m (5 ft), near the competition limit, to improve aerodynamic efficiency and provide additional stability and handling margins in the expected windy conditions.[1]

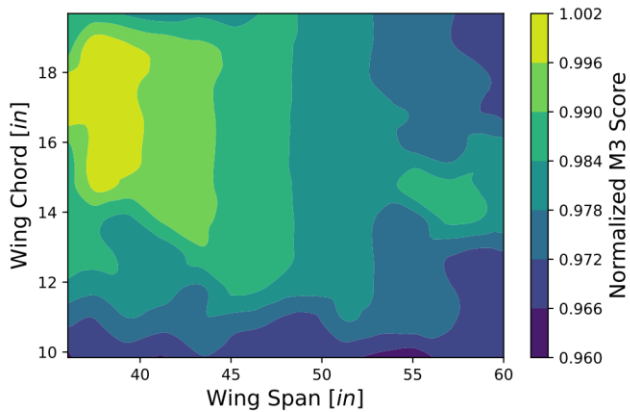


Figure 4: Normalized Mission 3 score as a function of wingspan and wing chord [1].

Final aircraft configuration

Brvinc has a wingspan of 1.50 m and a fuselage length of 1.44 m. The wing has an aspect ratio of 6.14, a root chord of 280 mm and a tip chord of 200 mm. The horizontal stabilizer has a span of 440 mm, and the vertical stabilizer has a span of 210 mm [1]. The final CAD assembly of Brvinc is shown in Figure 5.

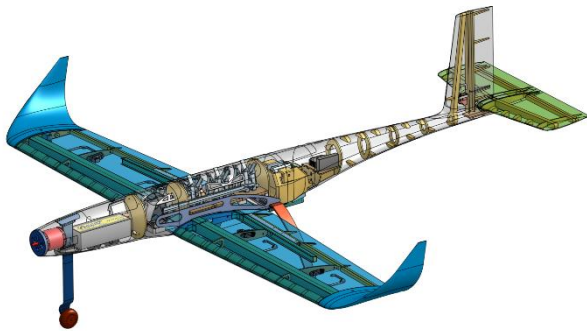


Figure 5: CAD assembly of the final Brvinc aircraft.

The fuselage is a monocoque composite structure that contains the avionics, banner mechanism and separate passenger and cargo compartments. The passenger compartment is positioned above the wing and accommodates three rubber ducks.

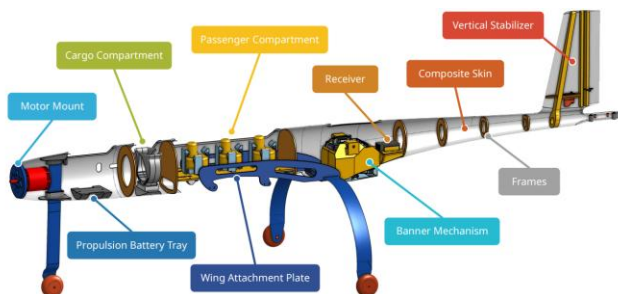


Figure 6: Fuselage layout and principal subsystem locations [1].

The cargo compartment is forward of the wing and accommodates one hockey puck. Each compartment has its own upper hatch. The propulsion battery is mounted in the

forward fuselage, while the banner mechanism is installed beneath the fuselage behind the main landing gear. The wing is attached to the fuselage through carbon-fibre ribs secured with four M4 bolts. A reinforced attachment plate and internal frames transfer loads between the wing, fuselage and landing gear. The layout of the main subsystems is shown separately in Figure 6.

Payload and banner systems

The passenger restraint uses compliant 3D-printed hooks. The hooks flex during loading and hold the ducks in place once installed. The cargo system uses circular clamps with integrated springs. A puck is pressed into the clamp and retained radially, while a funnel-shaped opening helps guide it during loading. These systems were developed to secure the payloads in flight while allowing rapid loading and unloading during the ground mission. The final passenger and cargo mechanisms are shown in Figure 7.



Figure 7: Manufactured payload mechanisms: cargo clamp and passenger restraint [1].

The banner is stored beneath the fuselage in a removable module. Fuselage-integrated guides align the module during installation, while electrical connectors link its servos to the aircraft's onboard control system. A spring-loaded pin locks the module in place. Two servo-operated pins perform separate release functions: one releases the folded banner for deployment, while the other releases the towline from the aircraft. A carbon-fibre tube supports the banner's leading edge, and a ballast weight helps maintain its vertical orientation in flight. Figure 8 shows the banner module and its deployment and release mechanisms.

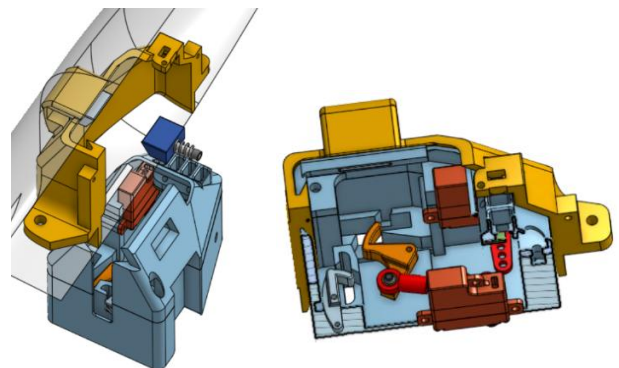


Figure 8: Removable banner module and its deployment and towline-release mechanisms.

The aircraft is powered by a Kontronik PYRO 700-45 brushless motor and an APC $15 \times 10E$ propeller. The motor is controlled by an APD 120F3 v2 electronic speed controller (ESC) and supplied by a 6S, 4500 mAh, 22.2 V LiPo battery. The ESC is mounted outside the fuselage to provide adequate cooling [1].

The avionics system is powered by a separate battery and uses a FrSky Tandem TD SR10 receiver. The aircraft's control surfaces are actuated by four Chaservo HV95 and two Chaservo HV75 servos [1]. The two Chaservo HV95 servos in the banner module are connected to the aircraft's avionics through electrical connectors and controlled by the main receiver.

MANUFACTURING OF THE AIRCRAFT

The fuselage, wing and horizontal stabilizer were manufactured using composite sandwich construction. Negative moulds for these parts were CNC-milled from Purenit MD 550. Alignment features in the moulds helped position reinforcements and internal components. Smaller moulds, including those for the landing gear and auxiliary parts, were 3D-printed.

The fuselage skin was manufactured using a wet-layup process with carbon- and glass-fibre layers and an aramid honeycomb core. Unidirectional carbon-fibre strips reinforced the structure longitudinally and around structural attachment points. The two fuselage halves were vacuum-bagged and cured for 24 hours under approximately 85% vacuum. Internal structures, such as ribs and the motor mount, were then installed using positioning jigs. The halves were joined with structural adhesive, and the fuselage was post-cured for 18 hours at approximately 54°C [1].

The wing skin was manufactured using a wet-layup process with biaxial carbon-fibre cloth, a 1.5 mm Airex core and an outer glass-fibre layer. Aramid cloth was incorporated at the flap and aileron hinges and sandwiched between two layers of glass-fibre cloth to prevent delamination. The front and rear spars were manufactured separately using resin infusion. Their webs were made from glass-fibre layers, while unidirectional carbon-fibre strips formed the spar caps. Before the wing halves were joined, the spars, ribs and servos were positioned inside the wing, as shown in Figure 9.

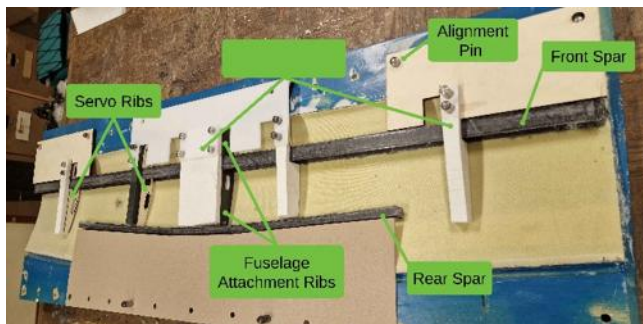


Figure 9: Positioning of the wing spars and ribs [1].

The front and main landing gear were manufactured from forged carbon fibre using polished, 3D-printed moulds. Smaller mechanisms, including the passenger, cargo and

banner components, were additively manufactured from ASA filament. Threaded heat-set inserts and embedded pultruded carbon-fibre rods were added to structural parts to improve their strength and simplify replacement.

The final competition banner was made from ripstop nylon. Its edges were folded and machine-sewn using a zigzag stitch and nylon thread. Hot-knife cutting was tested but not selected because the cut edges showed a greater tendency to tear.

PRELIMINARY TESTING

Banner Testing

Six banner fabrics were tested in a vertical wind tunnel to measure their aerodynamic drag and identify a suitable material for the competition aircraft. Each sample measured approximately 3.00×0.60 m. The test rig shown in Figure 10 used an S-beam load cell to measure drag force, while a pitot tube and pressure sensor were used to determine dynamic pressure [1].

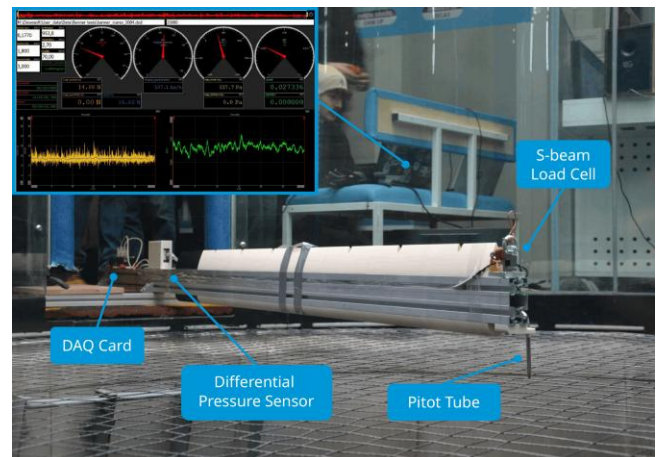


Figure 10: Vertical wind-tunnel test rig used to measure banner drag [1].

Measurements were recorded for 30 s at each airspeed to reduce the effects of rig oscillations and banner flutter. Among the materials tested initially, Icarex exhibited a relatively low drag coefficient and the smallest variation in measured drag force. Its drag coefficient at the estimated Mission 3 cruise speed was approximately 0.019, close to the value used in the initial mission model. The measured drag coefficients from this test series are shown in Figure 11. Although Icarex was initially selected as the banner material, subsequent testing showed that ripstop nylon outperformed it, leading the team to revise its material selection.

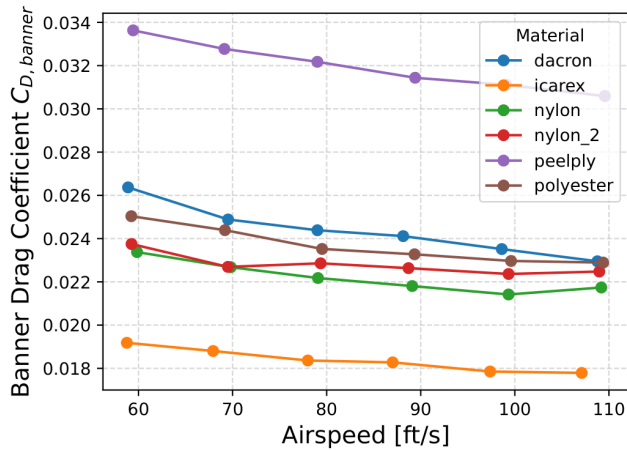


Figure 11: Measured drag coefficients of the banner fabrics tested [1].

Propulsion Testing

Two propulsion configurations were tested: a Kontronik PYRO 700-45 motor with an APC $15 \times 10E$ propeller, and a Kontronik PYRO 700-34 motor with an APC 18×12 propeller. Thrust, current, and airspeed were measured using a specially designed testing rig. Both configurations produced similar thrust across the operating range, but the PYRO 700-45 combination drew slightly less current. Its smaller propeller also allowed the landing gear to be shortened, thereby reducing aerodynamic drag.

The propulsion test setup used to examine the two engine and propeller combinations is depicted in Figure 12.

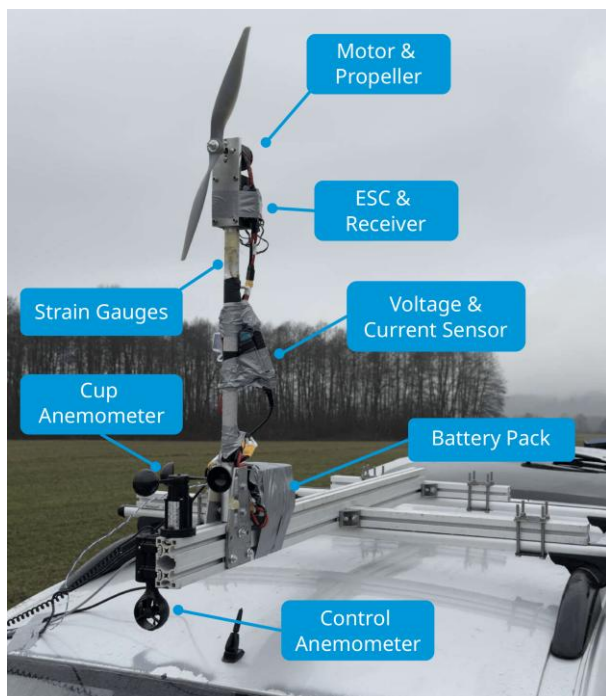


Figure 12: Propulsion test rig [1].

The measured current was higher than the value predicted by the initial simulations. The propulsion model was therefore updated to reflect the greater energy consumption. The APC

$15 \times 10E$ propeller and PYRO 700-45 motor were chosen for Brvinc based on the test results.

Structural Testing

Wing stiffness was assessed using a three-point bending test, with support positions selected to approximate the bending-moment distribution expected from aerodynamic lift; the test setup is shown in Figure 13. The applied load was gradually increased to the team-defined target of 667 N [1]. The wing withstood a maximum load of 698 N without permanent deformation or visible damage, exceeding the specified test load [1].

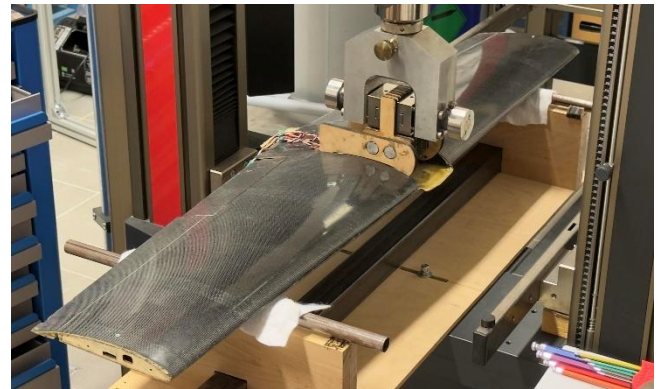


Figure 13: Three-point wing bending test [1].

Ground Mission Testing

Ground-mission performance was also practised and evaluated before the fly-off. The sequence included opening and closing the hatches, loading and unloading the passengers and cargo, and installing the banner. The average completion time was 26.3 s. The longest individual stage was installing the banner, which was determined to be the primary area for improvement.

FLIGHT TESTING

During testing, flight data were recorded using a CubePilot Cube Orange+ flight controller, a Here4 GPS and a Mauch power meter. The system ran ArduPilot firmware with the Plane BlackBox Logger build and stored the data on an SD card to allow for post-flight analysis and integration of data into simulations [1, 6].

Since the aircraft lacked a steerable nosewheel, flight testing started with low- and high-speed taxi runs at maximum take-off weight to assess rudder authority on the ground at low speeds. Simple pattern flights were then used to trim the control surfaces of the aircraft, familiarize the pilot with its flight characteristics, and determine the stall speed and characteristics. The rear landing gear flexed considerably during touchdown and taxiing in the early tests. Additional carbon-fibre layers were added to the landing gear to increase its rigidity. Subsequent taxi, take-off and landing tests showed no further issues, including testing on a grass runway.

Mission 2 test flights were compared with the mission simulation. The average lap time calculated from the flight logs was 33.4 s. The measured ground speeds along straight segments were slightly higher than the predicted values. A time offset was observed between the simulated and measured profiles; additional analysis attributed this to the pilot still becoming familiar with the aircraft during the early trials.

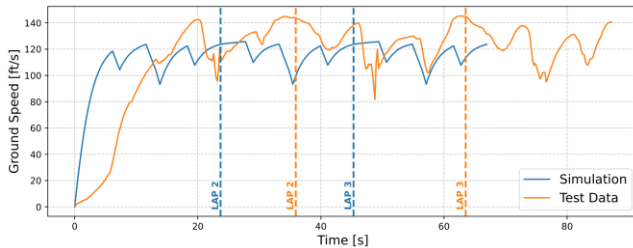


Figure 14: Simulated and measured ground-speed profiles during the Mission 2 test flight [1].

Because the team had no previous experience towing a banner in flight, the banner length was gradually increased from 100 to 550 cm to assess its effects on flight performance and handling. During the reported test flight with the 550 cm banner, shown in Figure 15, the average lap time was 59.7 s, and the aircraft remained stable and controllable throughout all phases of flight.



Figure 15: Brvinc towing the banner during flight testing.

Mission 3 test flights also showed that the banner's additional drag reduced ground speed, as reflected in the simulated and measured profiles in Figure 16.

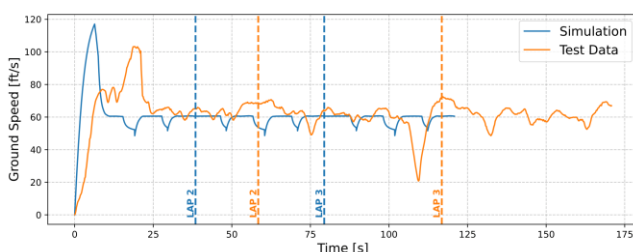


Figure 16: Simulated and measured ground-speed profiles during the Mission 3 test flight with the 550 cm banner [1].

The banner deployment and release mechanisms were also tested in flight. Initial tests showed that the banner could not be released while under tow load and that occasional

uncommanded deployments occurred. The team modified the deployment and release mechanisms to address these issues. During later testing, the towline became entangled with the rear landing gear during deployment. The aircraft entered an uncontrollable spin, resulting in the loss of the airframe. The incident exposed a potential failure mode that influenced further design changes before the competition fly-off; the damaged airframe is shown in Figure 17.



Figure 17: Crash aftermath [1].

FLY-OFF SUMMARY

The 2026 Design/Build/Fly competition was held in Wichita, Kansas, from 16 to 19 April, at the Textron Aviation Employees' Flying Club, with 89 university teams competing. Based on its design report, the University of Ljubljana's Edvard Rusjan Team was ranked second in the flightline starting order. The Edvard Rusjan Team and Brvinc at the competition are shown in Figure 18.

On the first day of the competition, the team passed technical inspection. It then completed the first Ground Mission attempt of the competition with a final time of 11 s.



Figure 18: Edvard Rusjan Team with Brvinc at the 2026 Design/Build/Fly competition in Wichita.

On the first day of flight missions, Brvinc completed Mission 1, a demonstration flight without payload, despite strong crosswinds on the competition site. Severe weather and a tornado warning forced precautionary evacuation of the site, postponing the team's Mission 2 attempt until the following day. At the start of the second competition day,

Brvinc completed Mission 2, carrying passengers and cargo. The team used the rest of the day to practise the Ground Mission in preparation for its final attempt to further improve the overall score.

On the final day, the team first improved its Ground Mission time to 6.6 s on its second and final attempt. Brvinc then completed Mission 3, towing the banner for six laps within the five-minute mission window, becoming the first aircraft of the competition to complete the mission successfully after University of Southern California (USC) failed to release their banner. This result put the team in first place, which it retained through the end of the competition. This was the Edvard Rusjan Team's third overall victory at the Design/Build/Fly competition and the first time the team had achieved first place in Wichita.

CONCLUSIONS

The Edvard Rusjan Team designed, manufactured and tested Brvinc for the 2026 AIAA Design/Build/Fly competition. Mission modelling and weighted decision matrices helped the team select an aircraft layout and payload strategy that balanced flight performance with the timed ground mission. Testing was then used to compare propulsion systems, select the banner fabric, assess wing strength and refine the banner mechanisms.

Brvinc completed the required missions and secured first place overall. The aircraft completed six laps while towing and successfully releasing the banner. The team reduced its ground-mission time from an average of 26.3 seconds during practice to just 6.6 seconds at the fly-off. Testing also identified areas for improvement, including landing-gear flexibility and banner-release reliability, which informed refinements to the final design.

The project showed how mission requirements can drive decisions across the aircraft, from wing sizing and propulsion to payload access and ground handling. The measurements collected during testing and competition provide a basis for future improvements to the team's simulation and testing methods.

ACKNOWLEDGMENTS

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