Content of 3-WP01 Advanced V2X communication for more efficient transportation

Coordinator of the WP

Czech Technical University, Faculty of Electrical Engineering, prof. Ing. Vladimír Havlena, CSc.

Participants of the WP

Herman Electronics, Dr. Ing. Ivo Herman

Skoda Digital, Dr. Ing. Daniel Pachner

FEE CTU, Dept. of Control Engineering, doc. Ing. Zdenek Hurak, PhD.

FEE CTU, Dept. of Computer Science, doc. Ing. Jiri Vokrinek, PhD.

FEE CTU, Dept. of Radioelectronics, prof. Ing. Jan Sykora, CSc.

Main Goal of the WP

Improved design of V2X communication unit hardware with high scalability, advanced localization and vehicle sensor fusion. The solution will communicate with municipal transport infrastructure (traffic light controllers) to provide priority for municipal transport (vehicles with predefined fixed routing) or first responders (vehicles with flexible trajectory planning). The software module will also support traction energy consumption minimization for trams.

Partial Goals for the Current Period

Selection of on-board unit hw, analysis of communication standards, design of core algorithms, collection of data and evaluation of core algorithms on simulated and real data.

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverables

- 3-WP01-001 | Advanced V2X communication unit with priority optimization, G-funk
  Due 12/2025 | CTU FEE 0.4 | Ivo Herman 0.6 |
- 3-WP01-002 | On board software modules for vehicle prioritization, R
  Due 12/2025 | CTU FEE 0.3 | Ivo Herman 0.4 | Skoda Digital 0.3 |
- 3-WP01-003 | Dispatch server software modules for vehicle prioritization, R
  Due 06/2026 | CTU FEE 0.8 | Ivo Herman 0.1 | Skoda Digital 0.1 |
- 3-WP01-004 | Evaluation of dispatch server optimization strategies by simulation, O
  Due 12/2025 | CTU FEE 0.8 | Ivo Herman 0.1 | Skoda Digital 0.1 |
- 3-WP01-005 | Pilot evaluation of on-board prioritization subsystem on V2X unit, O
  Due 12/2025 | CTU FEE 0.2 | Ivo Herman 0.7 | Skoda Digital 0.1 |
- 3-WP01-006 | Pilot evaluation of energy optimization of tram operation, O
  Due 12/2025 | CTU FEE 0.1 | Ivo Herman 0.1 | Skoda Digital 0.8 |
- 3-WP01-007 | Reporting and dissemination, O
  Due 06/2026 | CTU FEE 0.6 | Ivo Herman 0.2 | Skoda Digital 0.2 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-001 (Gfunk, Ivo Herman, Jan Sykora FEE CTU)

Advanced V2X communication unit with priority optimization

Improved design of V2X communication unit hardware with respect to optimal signal propagation, robust and efficient implementation on an operating system with high scalability and ability to process large number of messages. Basic solution will cover advanced localization and vehicle sensor fusion. For municipal transport and first responder vehicles, the unit will support prioritization and collaboration with dispatching server. In terms of radio propagation, the unit will be tested against a newly developed testbed, which will verify the unit's performance and compliance to standards (in V2X and/or 5G-V2X).

Due 12/2025 | CTU FEE 0.4 | Ivo Herman 0.6 | Skoda Digital 0.0 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-001

Advanced V2X communication unit with priority optimization

- Goals
  - Long range V2X communication with computation power for decentralized decision making (priority optimization, integration to ADAS)
  - Integrate new radio technology (ITS-G5 – Wi-Fi, LTE-V2X, 5G-NR) with run-time switching
  - Security to allow CC certification (tamper detection)
  - Design and implementation of laboratory testbed for radio air-interface of V2X communication systems based on IEEE 802.11p and 5G NR C-V2X

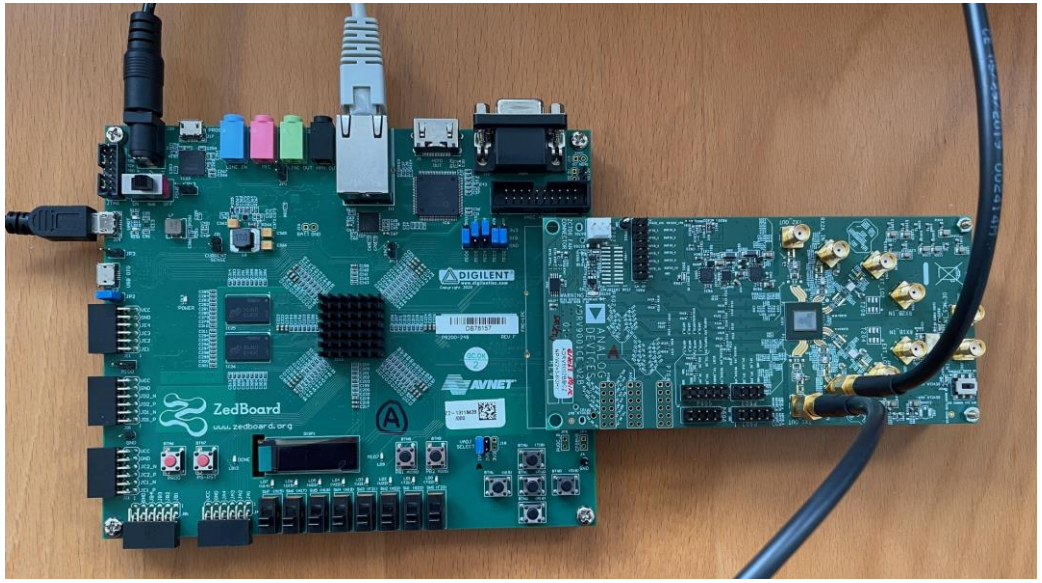
- Activities
  - Component selection for the new unit finished (i.MX8 series)
  - Design of testbed in progress
  - Basic hands-on experience with the new components

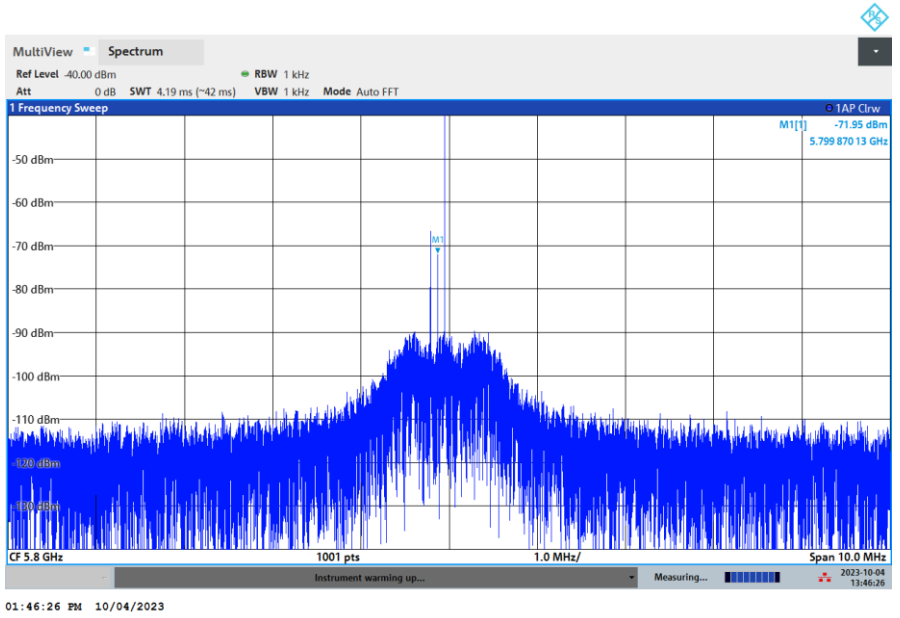
Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-001

Advanced V2X communication unit with priority optimization

- Results – test bed
  - RF platform ADRV9002 3-6 GHz 2x2 Transceiver
  - Baseband & control layer platform Xilinx Z7EV-7Z020 (ZedBoard)





Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-002 (R, Ivo Herman)

On board software modules for vehicle prioritization

Plug-in software modules for vehicle prioritization using V2X communication unit. The solution will communicate with municipal transport infrastructure (traffic light controllers) to provide priority for municipal transport (vehicles with predefined fixed routing) or first responders (vehicles with flexible trajectory planning). The software module will also support traction energy consumption minimization by providing departure time from stops and velocity profile to the next intersection.

Due 12/2025 | CTU FEE 0.3 | Ivo Herman 0.4 | Skoda Digital 0.3 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-002

On board software modules for vehicle prioritization

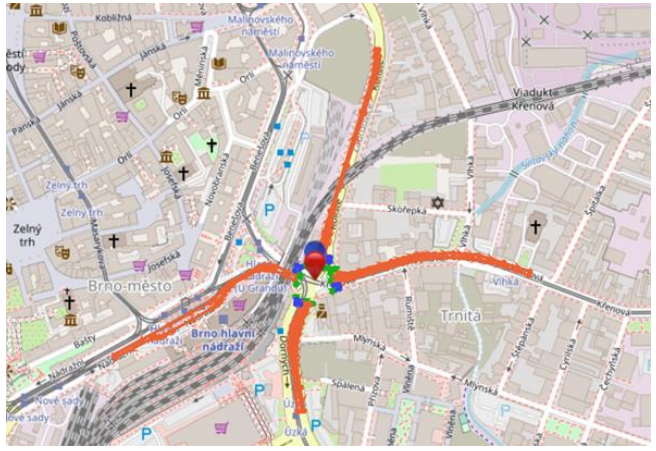
- Goals
  - Process all received information for better priority request control
  - Generate correct and norm-compliant request with reliable parameters (ETA)
  - Allow processing of traffic light controller response
  - Standardized solution integration to board computer (SREM/SSEM messages)
- Activities
  - Advanced MAPEM processing, basic ETA calculation
  - Automatic request, update and cancellation based on received MAP
  - Data logging
  - Standardization of VDV 435 – first on-board protocol for PT with direct support of V2X
  - Standardization of content and use of SREM messages – TLC vendors + C-ROADS EU

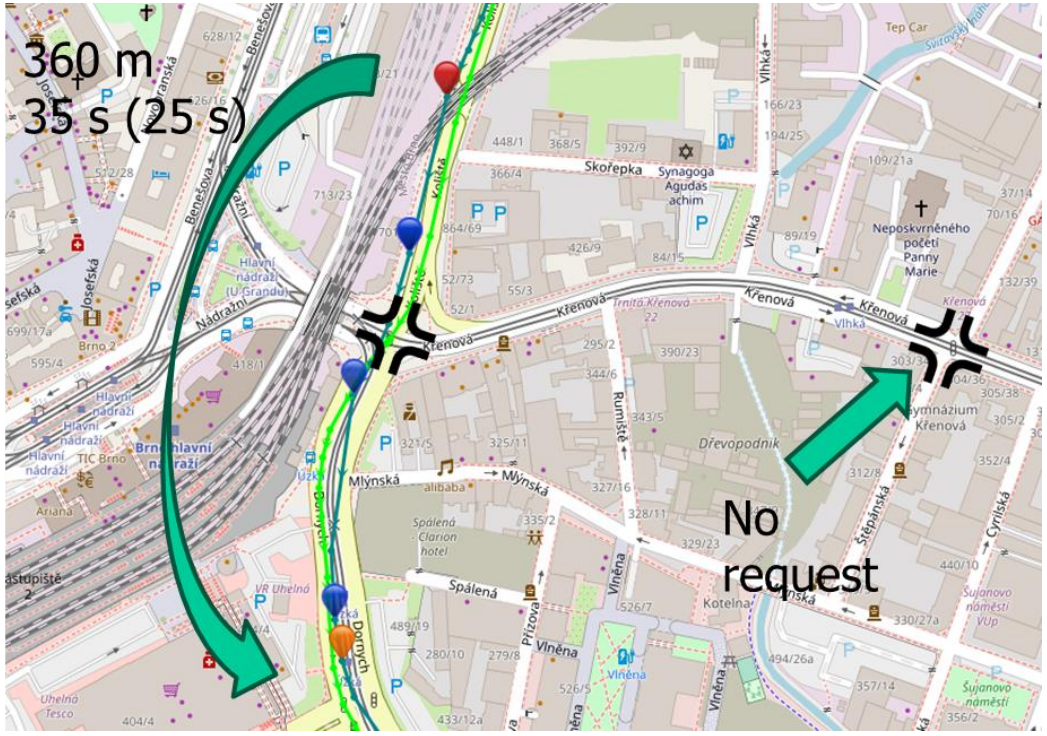
Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-002

On board software modules for vehicle prioritization

- Data sources
  - Own position and other states
  - Information about the trip (route, delay, planned stop)
  - Intersection topology, signal plan + queue lengths
  - Information from other vehicles
  - Data from dispatch server(s)





Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-003 (R, Jiri Vokrinek FEE CTU)

Dispatch server software modules for vehicle prioritization

Cloud level software for municipal transport / first responders trajectory optimization using intersection controller signal plan plans and other centrally available information. The optimization will combine data-centric approach based on archived historical data and AI methods, as well as analytical model-based approach.

Due 06/2026 | CTU FEE 0.8 | IvoHerman 0.1 | SkodaDigital 0.1 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-003

Dispatch server software modules for vehicle prioritization

- Goals
  - Analysis of legacy AI powered algorithms and tools (46 relevant tools/libraries/demos) for dynamic path/trajectory planning
  - Standardization of algorithms implementation to build re-usable software modules
  - Design of server-based software stack for vehicle prioritization / transport optimization

- Activities
  - Analysis of AI powered algorithms for dynamic path/trajectory planning running
  - Design of server-based software stack

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-003

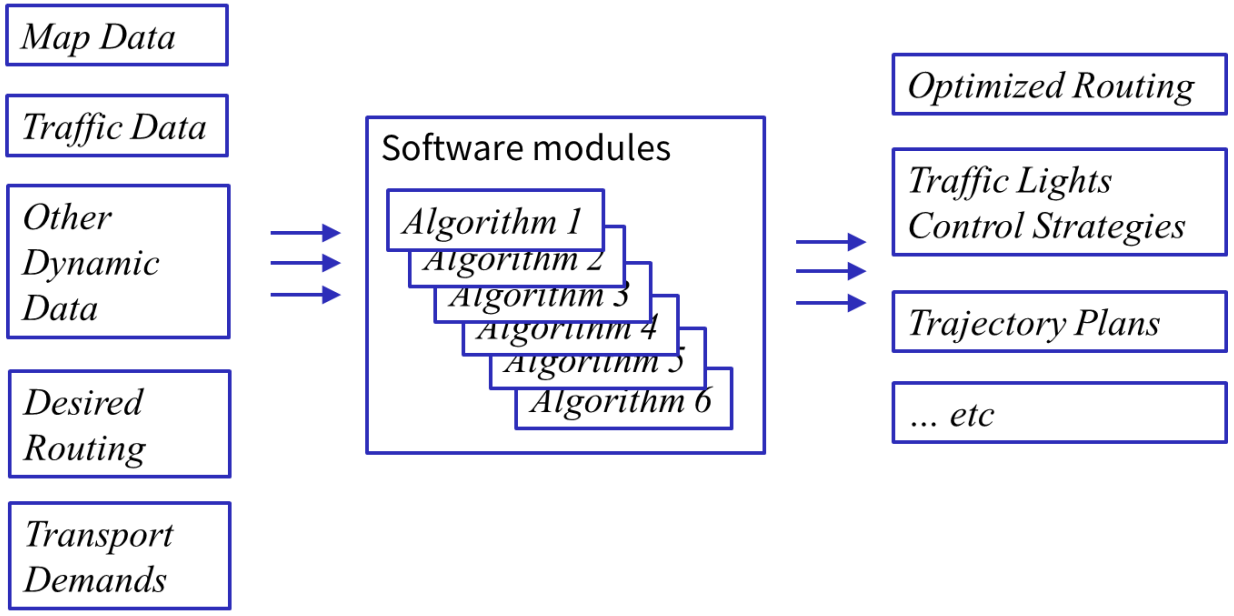
Dispatch server software modules for vehicle prioritization

Examples of legacy algorithms

- Multicriterial route planning
- Vehicle routing optimization
- Traffic flows optimization
- Multi-modal transport planning
- EV route planning
- Traffic capacity optimization

New algorithms for new use-cases

Architecture



Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-004 (R, Jiri Vokrinek FEE CTU)

Evaluation of dispatch server optimization strategies by simulation

This simulation-based feasibility study will provide evaluation of alternative planning and optimization strategies and collaboration with intersection controllers using simulation models. Models will be calibrated using historical data. Short-term and predictive long-term strategies will be evaluated. The model will also provide a "what if" analysis tool for municipal dispatch operators.

Due 12/2025 | CTU FEE 0.8 | Ivo Herman 0.1 | Skoda Digital 0.1 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-004

Evaluation of dispatch server optimization strategies by simulation

- Goals
  - Validate optimization strategies for selected use-cases by simuation
  - Provide scalable tool covering micro to macro simulation (from vehicle to traffic flow)

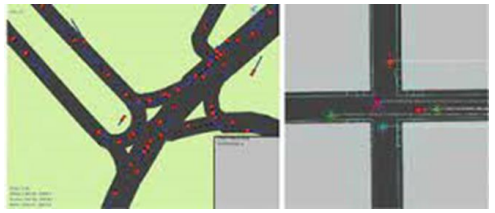
- Activities
  - Development of simulation concepts
  - General use-cases identification
  - Data integration preparation, import/export tools refactoring/generalization
  - Review of SOTA simulation platforms (6+) to be integrated
  - Design of simulation stack to be implemented (micro vs macro sim., number of vehicles, scale of the traffic system, etc.)

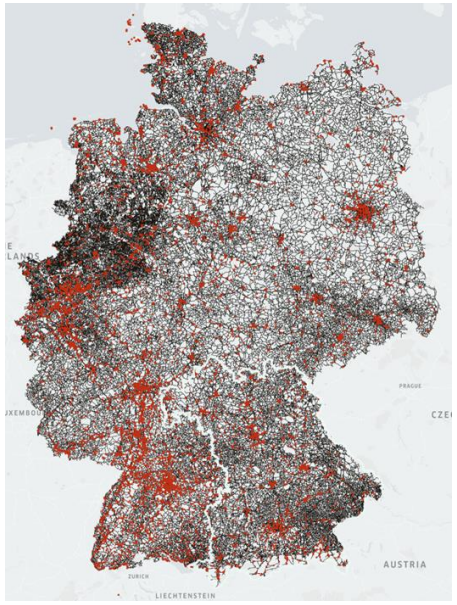
Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-004

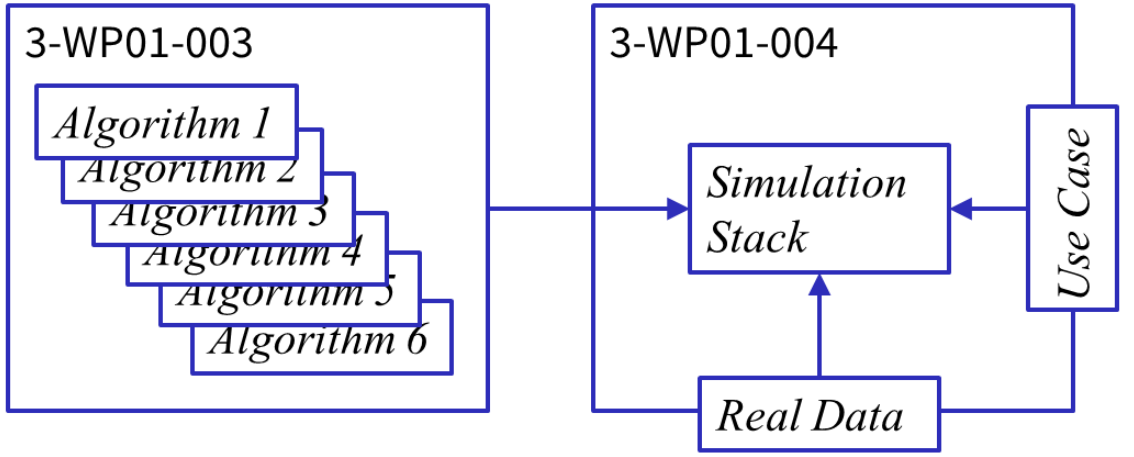
Evaluation of dispatch server optimization strategies by simulation

Scaling





Architecture



Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-005 (R, Ivo Herman)

Pilot evaluation of on-board prioritization subsystem on V2X unit

This feasibility study will provide real-life evaluation of pilot application of on-board software module for vehicle prioritization for municipal transport and first responders in Brno city and comparison of the performance with historical data.

Due 12/2025 | CTU FEE 0.2 | Ivo Herman 0.7 | Skoda Digital 0.1 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-005

Pilot evaluation of on-board prioritization subsystem on V2X unit

- Goals
  - Evaluation of pilot operation of on-board software module for vehicle prioritization for municipal transport and first responders in Brno and Chomutov city
  - Comparison of the performance with historical data
- Activities
  - Two pilot sites running, one in preparation
  - Discussion with partners in progress

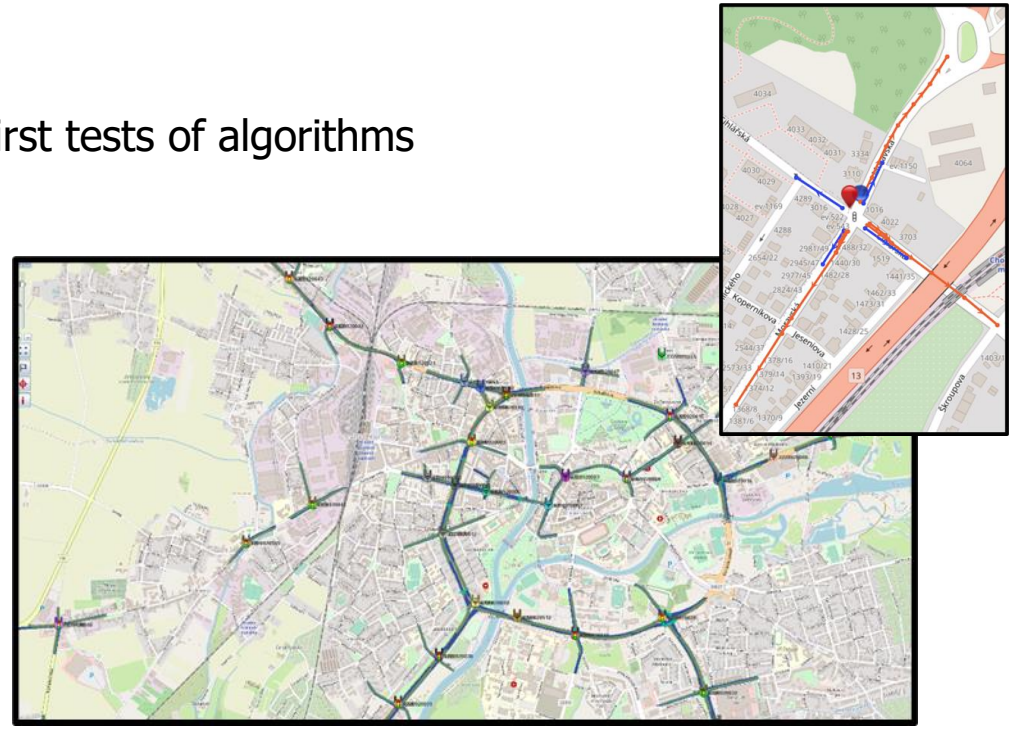
Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-005

Pilot evaluation of on-board prioritization subsystem on V2X unit

Pilot sites

- Chomutov (running)
  - RSU + OBU (8) by Herman, simple intersection, ideal for first tests of algorithms
- Hradec Králové (running)
  - All intersections in the city (40)
  - All public transport vehicles (130)
  - Several emergency vehicles (3)
  - Several roadwork vehicles (7)
  - **Awarded in C-ROADS Urban C-ITS Contest**
- Ulm (DE) (planned)
  - Full-scale test against 3rd party RSUs (Swarco, Yunex)
  - Full integration to BC (Trapeze) using the new protocol



Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-006 (O, Daniel Pachner, Skoda Digital)

Pilot evaluation of energy optimization of tram operation

This feasibility study will provide real-life evaluation of pilot application of on-board software module for minimization of tram traction energy consumption based on communication with intersection controllers. Target algorithm will be used in driver assistant system advising the driver when to start from the tram stop and how to control the speed to pass intersections freely.

Due 12/2025 | CTU FEE 0.1 | Ivo Herman 0.1 | Skoda Digital 0.8 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-006

Pilot evaluation of energy optimization of tram operation

- Goals
  - Evaluation of impact of prioritization on tram energy efficiency
  - Performance of on-board software module for minimization of traction energy consumption
  - Solution based on V2X communication with intersection controllers
- Activities
  - V2X unit selection (collaboration with 4-WP01 / Skoda Digital)
    - Opportunity to evaluate V2X unit from Herman Electronics
  - Diploma thesis V. Fanta – Energy efficient control of rail vehicles (FEE CTU)
    - Continues as a PhD student
    - Thesis topic aligned with NCC2 project objectives

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-007 (O, Vladimir Havlena, FEE CTU)

Reporting and dissemination

Interim reports on individual project milestones, publications in journals and conferences, diploma and PhD theses.

Due 06/2026 | CTU FEE 0.6 | Ivo Herman 0.2 | Skoda Digital 0.2 |

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Deliverable 3-WP01-007

Reporting and dissemination

- Bachelor and diploma theses
  - Jakub Kašpar: Algoritmy pro palubní odhadování pohybových stavů vozidla pomocí multisenzorické fúze (bakalářská práce FEL ČVUT, 2023)
  - Matěj Kříž: Platforma pro prototypování algoritmů pro palubní odhadování pohybových stavů vozidel multisenzorickou fúzí (bakalářská práce FEL ČVUT, 2023)
  - Vít Fanta: Energeticky efektivní řízení kolejových vozidel (diplomová práce FEL ČVUT, 2023)
- Other publications
  - Standardization of VDV 435 – first on-board protocol for PT with direct support of V2X
  - Standardization of content and use of SREM messages – TLC vendors + C-ROADS EU

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Current State of Deliverables and Fulfillment of Goals

- No binding deliverables (Gfun, R) in 2023
- 5+2 deliverables O (publications)
- Goals for 2023 in progress, no major delays
  - HW platform selection closed and purchased (OBU, test bench)
  - First hands-on experience
  - Design of software architecture and core algorithms
  - Collection of real time data for performance evaluation started

Added Value of 3-WP01 results

- Saving on a single crossing with V2X based priority (controlled departure from the stop) exceeds 150000 CZK/year (calculated by DP Brno, crossing Mendel square x Pekarska street)
- V2X based preference based on SREM/SSEM is becoming C-ROADS industrial standard. It implies big market potential for early adopters.

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Assessment of the Contribution of Deliverables

- V2X technology developed in 3-WP01 by Herman Electronics partner will be used in 4-WP01 by Skoda Digital partner
- Advanced localization developed in 4-WP01 by academic partners will be also used in OBU development in 3-WP01 (scaled down version, no Lidar and optical sensors)

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Assessment of the Formal/Administrative Goals of the Work Package

	Herman Electronics	Skoda Digital	FEE CTU
Finance	**OK**	**OK**	**OK**
Commercialization	**N/A**	**N/A**	**N/A**
Deliverables	**N/A**	**N/A**	**OK**

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Acknowledgment

This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Center II, project # TN02000054 Božek Vehicle Engineering National Center of Competence (BOVENAC).

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Abstracts of publications

Jakub Kašpar: Algoritmy pro palubní odhadování pohybových stavů vozidla pomocí multisenzorické fúze (bakalářská práce FEL ČVUT, 2023)

Byl navržen a otestován lokalizační algoritmus určený pro tramvaje. Algoritmus využívá rozšířeného Kalmanova filtru k fúzi měření z přijímače satelitní navigace, inerciální měřicí jednotky a odometrie.

An extended Kalman filter based localisation algorithm intended for trams has been developed. The algorithm fuses measurements of satelite based navigation system, inertial measurement unit and wheel encoder odometry.

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Abstracts of publications

Matěj Kříž: Platforma pro prototypování algoritmů pro palubní odhadování pohybových stavů vozidel multisenzorickou fúzí (bakalářská práce FEL ČVUT, 2023)

Tato práce se zabývá vývojem jednodeskové platformy pro sběr dat ze senzorů pohybových stavů vozidel a pro prototypování algoritmů, které tato data fúzují. Tato platforma by měla zjednodušit záznam dat a standardizovat jejich formu pro zlepšení znovupoužitelnosti pro další projekty. Dále se zabývá dalšími podklady pro snadnější implementaci algoritmů, jako je práce s mapovými podklady a geografickými referenčními systémy.

This thesis describes development of embedded platform for recording data from vehicle motion state sensors and for development of algorithms using fusion of such data on board vehicles. This platform should simplify recording and standardize data format for reusability in future projects. The thesis also describes other improvements including algorithm simplifications concerning usage of maps and geographic reference systems.

Content of 3-WP01 Advanced V2X communication for more efficient transportation

Abstracts of publications

Vít Fanta: Energeticky efektivní řízení kolejových vozidel (diplomová práce FEL ČVUT, 2023)

Cílem této práce je představit problém optimálního řízení vlaku a implementovat open-source softwarový balíček, pomocí něhož je jej možno řešit. Řešením je rychlostní profil, který bere v úvahu trakční limity vlaku, celkový čas cesty a výškový profil tratě a zároveň minimalizuje celkovou vynaloženou energii. Optimální strategie spočívá v přepínání několika jízdních režimů: maximální trakce, držení rychlosti, optimální brzdění, výběh a maximální brzdění. Na ploché trati má optimální strategie podobu maximální trakce – (držení rychlosti) – výběh – maximální brzdění. Na obecné trati může docházet k většímu množství přepnutí kvůli příliš strmým úsekům. Řešení bylo implementováno v jazyce Julia a je dostupné veřejnosti v podobě balíčku na GitHub. I přes to, že je program obecně funkční a příklady výpočtu jsou uvedeny. Některé funkcionality stále chybí (především možnost zahrnout rychlostní omezení). Současné řešení je však možno dále vyvíjet díky jeho open-source povaze.

The goal of this thesis is to present the problem of optimal train control and implement an open-source software package able to solve it. The solution is a speed profile which takes train's traction capabilities, total journey time and the track gradient into account while minimising the total required energy.

The optimal control strategy is a switching strategy between a small number of modes: Maximum Power, Cruising, Optimal Braking, Coasting and Maximum Braking. On a flat track, the optimal strategy has the form Maximum Power – (Cruising) – Coasting – Maximum Braking. On a general track, more switching can occur due to the steep uphill and steep downhill sections of the track. A solution has been implemented in the Julia programming language and is available to the public in a form of a package accessible on GitHub. The solution is functional and examples of speed profile calculation are shown. Some features are still missing, most notably inclusion of speed limits. Functionality of the implemented solution can be further developed thanks to its open-source nature.