UNOFFICIAL MACHINE TRANSLATION

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The use of FRMCS systems in rail transport, including dedicated channels in the 900 MHz and 1900 MHz bands

Prepared for the Ministry of Industry and Trade

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Národní plán obnovy

Revision history

Version	Change	Author	Date
A.3	Terms of reference and list of supporting documents, division into chapters, draft chapters on the use of the 1900 MHz band and migration scenarios	Boček	28 July 2024
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Grant Thornton

Contents

Executive Summary

This study examines the specific conditions for implementing the FRMCS system in the Czech Republic, particularly on the network of the majority railway infrastructure manager, Správa železnic s.o., taking into account existing strategic plans for the development of rail transport in the Czech Republic, as well as the technical and economic conditions for the construction of the GSM-R system. In addition to written and online sources, which are cited collectively in Chapter 5, the study **incorporates the views of members of the working group, comprising representatives of the contractor, freight and passenger operators affiliated with ŽESNAD and SVOD Bohemia, Správa železnic s.o., the Ministry of Transport, the Ministry of Industry and Trade, and Czech delegates to the international organisations ERJU and UNIFE**.

A list of applications defined in the user requirements for the FRMCS system (FRMCS URS), drawn up by the UIC and forming the basis for FRMCS standardisation, was adopted as representative of both current and future applications used to support railway operations. The user requirements also classify these applications in terms of criticality. For the purposes of this study, **a** separate **translation of the relevant sections of the FRMCS URS** was prepared, taking into account established Czech railway terminology and the specific characteristics of Czech railway operations, as presented to the working group by representatives of the Ministry of Transport and the SVOD/ŽESNAD association. This translation, together with an updated glossary of relevant terms and definitions, forms part of the annexes to this study. The annex will be submitted to the European Commission's Translation Service in Luxembourg, where it will be used **to refine the translation of EC regulations relating to railways into the national language version**. Details of this output are summarised in Chapter 1.2 of this study. Based on the list of applications, a questionnaire was drawn up to map their prospects and significance for the railway sector in the Czech Republic. The methodology used for the questionnaire is taken from an earlier study prepared for the ERA in 2016, meaning that its findings allow for a comparison of the views of representatives of the Czech railway sector with the European context. Chapter 1.1 of this study is devoted to the evaluation of the significance of the applications based on the questionnaire.

Chapter 2 is devoted to the potential coverage of the railway network by the FRMCS system. Each sub-chapter, devoted to individual RMR bands, MNO bands (Chapter 2.3) and other radio access options (Chapter 2.4), summarises the technical conditions for their use, the basic characteristics of signal propagation and the relationships with other bands, taking into account possible mutual interference. Specifically for the 900 MHz band (Chapter 2.1), coexistence with GSM-R (Chapter 2.1.3) is discussed; within Chapter 2.2, concerning the 1900 MHz band, the specifics of using TDD bands, as well as the limitations and benefits of its potential use, are discussed. The main conclusion of the analysis is that **densification of** the FRMCS **base station** (gNB) **network** is necessary for the deployment of the **1900 MHz** band, but **will not reach the commonly envisaged 100 per cent**; and, given the longer-term prospects for FRMCS use, the use of this band should not be excluded from the planned procedures.

The communication requirements, specifically the throughput of the radio access network, were taken from UIC and ERA working documents and technical reports and compared with the results of NR RAN simulations reported in the technical report ETSI TR 103 554-2 [3]. The results of this comparison, presented in Chapter 2.6 of this study, show that **none of the RMR bands alone will be sufficient to support the full range of critical applications**, and it will be necessary to gradually expand the FRMCS system to cover both bands, or to transfer part of the communications to bands operated by MNOs. It would be advantageous to take this target state into account when optimising the costs and logistics of the initial migration steps.

The next section of this study is devoted **to the evaluation of the migration scenarios under consideration**. The evaluation proceeds from theoretical scenarios, taken from an earlier study prepared for the ERA in 2016, to sub-variants reflecting the specific characteristics of the current situation in the Czech Republic. The individual variants cover the sequence of migration for infrastructure and rolling stock, the transition to bands outside the 900 MHz range, and the impact of incompatibilities within the FRMCS or in relation to ETCS, assessed for a single network (Chapter **Error! Reference source not found.**) and the sequence of migration in relation to a neighbouring larger railway network, taking into account the conditions of cross-border operations (Chapter 3.5). The evaluation of the scenarios also includes a comparison of their costs using a model adapted from an earlier study prepared for the ERA and modified to suit the specific conditions of the Czech railway network in the 2020s. The main conclusion of the comparison is that **the scenario involving dual FRMCS/GSM-R terminals**, installed on rolling stock, is indeed more favourable to operators in terms of investment and more resilient to external factors, such as technical differences and time lags in migration across neighbouring railway networks; however, it is **unfeasible due to a lack of time reserves** for the piloting and approval of on-board equipment. Chapter 3.3 of the scenario assessment includes **a discussion of the motivations of individual stakeholders** based on their responses to the questionnaire, and a comparison of these results with a survey from an earlier study conducted for the ERA amongst Western European railway administrations and operators.

The evaluation of the options and the content of the discussion within the working group responsible for preparing the study have, amongst other things, led to **proposals for changes to the legislative framework**, relating primarily to **the stabilisation of the regulatory environment, vehicle certification and the conditions for public financial support for migration**, which are summarised in Chapter 4. The aim of these proposed measures is to prevent the negative impacts of previous migration campaigns – specifically the introduction of ETCS-only operation – which had a significant impact on the profitability of migration for operators and are one of the reasons for the low level of motivation among entities in the Czech railway sector to switch to FRMCS.

Management summary

This study examines the specific conditions for the implementation of the FRMCS system in the Czech Republic, particularly on the network of the majority infrastructure manager, Správa železnic s.o., in light of existing strategic plans for the development of rail transport in the Czech Republic, as well as the technical and economic conditions for the construction of the GSM-R system. In addition to written and online sources, cited in Chapter 6, **the study incorporates the views of members of the working group, comprising representatives of the author, freight and passenger operators affiliated with ŽESNAD and SVOD Bohemia, Správa železnic s.o., the Ministry of Transport, the Ministry of Industry and Trade, and delegates from the Czech Republic to the international organisations ERJU and UNIFE**.

The list of applications defined in the user requirements for the FRMCS system (FRMCS URS), processed by the UIC and forming the basis of FRMCS standardisation, was taken as representative of existing and future applications used to support railway operations. At the same time, the user requirements classify these applications in terms of criticality. For the purposes of the study, an **in-house translation of the relevant parts of the FRMCS URS** was prepared, taking into account established Czech railway terminology and the specific operational characteristics of the Czech railway system, as presented to the working group by representatives of the Ministry of Transport (MD) and the SVOD/ŽESNAD associations. The actual translation, together with an updated glossary of relevant terms and definitions, forms part of the appendices to this study. The annex will be submitted to the EC Translation Service in Luxembourg, where **it will be used to refine the translation of the EC railway regulations into the national language version**. The details of this output are summarised in Chapter 1.2 of the present study. Based on the list of applications, a questionnaire was drawn up to assess their relevance and importance for the railway industry in the Czech Republic. The methodology used in the questionnaire is based on an earlier study prepared for the ERA in 2016; its findings will therefore enable us to compare the views of Czech railway representatives with the European context. Chapter 1.1 of the present study is devoted to evaluating the importance of the applications based on the questionnaire.

Chapter 3 is devoted to the potential coverage of the railway network by the FRMCS system. In each subsection, dedicated to individual RMR bands, MNO bands (Chapter 2.3) and other forms of radio access (Chapter 2.4), the technical conditions for their use, basic characteristics of signal propagation and relationships with other bands with regard to potential mutual interference are summarised. Specifically for the 900 MHz band (Chapter 2.1), coexistence with GSM-R (Chapter 2.1.3) is discussed; within the framework of Chapter 2.2, which is dedicated to the 1900 MHz band, the specifics of using bands with TDD, as well as the limitations and benefits of its potential use, are examined. The main conclusion of the analysis is that **densification of the network of base stations (gNB)** of the FRMCS system is necessary for the deployment **of the 1900 MHz band**, but it **will not reach the commonly assumed 100 per cent;** furthermore**,** with regard to the longer-term outlook for the FRMCS, the use of this band should not be excluded from the planned procedures.

The communication requirements, specifically the throughput of the radio access network, were taken from UIC and ERA working papers and technical reports and compared with the results of the NR RAN simulations, as reported in the ETSI technical report TR 103 554-2 [3]. The results of this comparison, presented in Chapter 2.6 of this study, show that, to support the communication requirements of the entire set of critical applications, no single RMR band will be sufficient on its own; it will be necessary to gradually develop the FRMCS system to utilise an overlap of both bands, or to transfer part of the communication to the bands operated by the MNO. It will be beneficial to take this target state into account in order to optimise the costs and logistics of the initial migration steps.

The next section of this study is devoted to the **evaluation of the migration scenarios under consideration**. The evaluation proceeds from theoretical scenarios taken from an earlier study prepared for ERA in 2016 to sub-variants reflecting the specific circumstances of the current situation in the Czech Republic. The individual scenarios cover the sequence of migration for infrastructure and on-board equipment, the transition to bands outside the 900 MHz range, and the impact of incompatibilities within the FRMCS or in relation to ETCS, as assessed for a single network (Chapter 3.4), as well as the sequence of migration in relation to the neighbouring larger railway network, taking into account the conditions of cross-border traffic (Chapter 3.5). The evaluation of the scenarios also includes a comparison of their costs using a model derived from an earlier study prepared for the ERA and adapted to the current conditions on the Czech railway network in the 2020s. The main conclusion of the comparison is that **the scenario involving dual FRMCS/GSM-R terminals,** installed on rolling stock, is more cost-effective for operators and more resilient to external factors, such as differences in equipment and shifts in migration timelines in neighbouring railway networks; however, it is **unfeasible due to the lack of time allowed** for piloting and approval of on-board equipment. The evaluation of the scenarios includes a **discussion of the motivations of individual participants** based on their responses to the questionnaire in section 4.3 and a comparison of these results with a survey of Western European railway administrations and operators carried out for ERA in an earlier study.

The evaluation of the options and the content of the discussion within the working group responsible for preparing the study led, amongst other things, to **proposals for changes to the legislative framework**, mainly concerning the **stabilisation of the regulatory environment for technical regulations, vehicle certification and the conditions for public financial support for migration**, which are summarised in Chapter 4. The aim of these proposed measures is to prevent the negative impacts of previous migration campaigns – specifically the introduction of exclusive ETCS operation, which had significant impacts on the profitability of migration for railway undertakings and is one of the reasons for the minimal motivation among Czech railway sector entities to switch to FRMCS.

Abbreviations used

3GPP	*Third Generation Project Partnership* – an association of organisations established to standardise third-generation mobile communications, continuing its activities for subsequent generations as well
4G LTE	*Fourth Generation Long Term Evolution* – a term for fourth-generation mobile communication technologies
5G NR	*Fifth Generation New Radio* – the designation for fifth-generation access radio technologies
5GC	*Fifth Generation Core* – a collective term for the technical components forming the core of a fifth-generation mobile communications network
5GS	*Fifth Generation System* – a collective term for the fifth-generation mobile communications network and technical infrastructure
5QI	*5G Quality Indicator* – an element of the mobile access control protocol signalling the required transmission quality class
ACLR	*Adjacent Channel Leakage* Power Ratio – spurious emissions into an adjacent channel
AP	*Access Point* – an access point for a communication service; in this context, specifically a component of a WLAN network that communicates with end terminals
ATO	*Automatic Train Operation* – a general term for a technical system for the automatic control of train movement
ATP	*Automatic Train Protection* – a general term for train safety systems
BL	*Baseline* – a term denoting the stable core of performance functions and other characteristics of ERTMS subsystems
BS	base station of a mobile communications system
CAPEX	*Capital Expenditure* – investment costs
CBA	*Cost-Benefit Analysis* – a methodology for project evaluation
CCTV	*Closed-Circuit Television* – a term used to describe a television or video system designed for specific private use, usually for security surveillance
CEPT	*European Conference of Postal and Telecommunications Administrations* – a European association of postal and telecommunications administrations, ensuring commercial, operational and legislative cooperation and technical standardisation
CU	*Control Unit* – a component of the 5G NR architecture that implements the remote logical layer and controls the gNB for a DU operating locally or remotely
DCS	*Dynamic Channel Selection* – a mechanism for selecting an operating frequency in DECT systems
DL	*downlink* – the direction from the network to the mobile terminal
DMR	*Digital Mobileland Radio* – the designation for a narrowband digital radio communication system in accordance with the ETSI TS 102 361 series standard
DU	*Distributed Unit* – a component of the 5G NR architecture that remotely implements the physical layer of transmission for the gNB
ECC	*Electronic Communications Committee* – an association of countries under the CEPT, responsible for developing policies and regulations for electronic communications within the European area
EDOR	*ETCS Data Only Radio* – a data modem for the GSM-R system used for ETCS (generally ATP) communication
EIRP	*Equivalent Isotropically Radiated Power* – the transmitted power of a radio interface radiated in all directions
EC	European Commission
eMBB	*Enhanced Mobile Broadband* – a term used to describe 4G/5G network services optimised for high transmission capacities
EP	European Parliament
ERA	*European Union Agency for Railways* – an agency established by the EU to develop and harmonise the European railway system; among other things, it acts as the pan-European body responsible for approving railway components
ERC	*European Research Council* – a European organisation for research funding

ERJU	*Europe's Rail Joint Undertaking* – a joint venture between the EU and private companies, tasked with supporting research and development of innovative solutions for the European railway sector; the successor to the Shift2Rail Joint Undertaking
ERTMS	*European Rail Traffic Management System* – a comprehensive system for train control and safety, critical voice communications and the associated radio communications infrastructure
ETCS	*European Train Control System* – a unified European rail traffic control system defined by European standards, comprising critical voice and data services for train safety and control
ETSI	*European Telecommunications Standards Institute* – a European non-profit organisation responsible for the development and management of telecommunications and radio communications standards
EUSPA	*EU Space Programme Agency* – the EU agency responsible for the development, operation and support of satellite technology applications
FDD	*Frequency Division Duplex* – a method of separating transmission directions using frequency multiplexing in bands with sufficient spacing
FR	France (international code according to ISO 3166-1)
FR1/FR2	*Frequency Range 1 / 2* – frequency ranges used for railway communications with fundamentally different characteristics
FRMCS	*Future Railway Mobile Communication System* – the successor to GSM-R within the ERTMS system, based on 5th-generation mobile networks
FUP	*Fair User Policy* – a mechanism for allocating limited network capacity amongst users, typically by throttling their speed once their data allowance has been exhausted
GEO	*Geostationary Earth Orbit* – a system of satellites orbiting in geostationary orbit
gNB	*Generalised Node B* – a node in the 5G RAN that provides the link between the mobile terminal (MT) and the network core, analogous to the base station (BS) in older standards
GNSS	*Global Navigation Satellite System* – a general term for a satellite navigation system, independent of its provider and specific parameters
GoA	*Grade of Automation* – the level of automation in an automatic train control system
GPS	*Global Positioning System* – a specific satellite navigation system operated by the US Department of Defence
GS	*Ground Station* – a component of a satellite system that provides centralised communication with the system's ground-based components and other networks
GSM-R	*Global Mobile Radio – Railway* – a second-generation mobile communications system adapted for use in the railway sector
HAPS	*High-Altitude Platform Station* – a component of a communications system located on an aircraft, other than satellites
HARQ	*Hybrid Automatic Repeat Query* – a mechanism for correcting block transmission errors, using both on-demand block repeats and self-correcting (forward) codes
HD	*High Density* – high resolution, in this context referring to the resolution of a television image (1920 x 1024 pixels)
HV	traction vehicle
HW	*hardware* – the technical components of an information and communications system
ID	identifier
IM	*Infrastructure Manager* – a general term for a role within the railway sector
IMS	*IP Multimedia Subsystem* – an application layer on top of mobile transport providing standardised multimedia services as defined by 3GPP
IoT	*Internet of Things* – a term for machine-to-machine communication over a mobile network, distinct from communication between human users
ISD	*Inter-Site Distance* – the distance between transceivers in neighbouring cells of a radio communication system
ISL	*Inter-Satellite Link* – a type of link utilising line-of-sight communication between satellites
ITU-R	*International Telecommunication Union – Radiocommunication Sector* – an international standardisation body, the section responsible for radiocommunications

LAN	*Local Area Network* – a term for a network providing data services on a local scale, specifically with a control and data layers in accordance with Ethernet standards
LEO	*Low Earth Orbit* – a system of satellites orbiting at low altitude
LoS	*Line of Sight* – radio communication requiring direct line of sight
MAC	*Medium Access Control* – the process of accessing a shared physical communication medium, specifically the radio interface of mobile networks
MCX	*Mission Critical Anything* – a collective term for critical services provided by networks based on 3GPP standards
MD	Ministry of Transport of the Czech Republic
MEO	*Medium Earth Orbit* – a system of satellites orbiting in medium Earth orbit
MIMO	*Multiple-Input Multiple-Output* – a term used to describe spatial division technologies for radio transmission
mMTC	*Massive Machine Type Communication* – a term used to describe 4G/5G network services optimised for communication with a large number of machine users
MNO	*Mobile Network Operator* – an operator of a mobile communications network, specifically a network providing public services
MOCN	*Multiple Operator Core Network* – a shared mobile network architecture with a common
MPO	Ministry of Industry and Trade of the Czech Republic
MT	mobile terminal – a subscriber device for mobile radio access, abbreviated as UE in English texts
NB-IoT	*Narrow Band IoT* – IoT operating on narrowband radio transmission
NLoS	*Non-Line of Sight* – radio communication without direct line of sight (via reflected signals)
NPV	*Net Present Value* – a comprehensive indicator of economic value over a longer period; used in the study to denote liabilities without a negative sign
NTN	*Non-Terrestrial Networks* – a collective term for networks whose base stations (BS) or access points (AP) are not located on the Earth's surface
OFDM	*Orthogonal Frequency Division Multiplexing* – a method of modulating digital signals onto a group of narrowband carriers
OPEX	*Operational Expenditure* – operating costs
P25	designation of a narrowband digital radio communication system in accordance with the APCO-25 standard
PDCP	*Packet Data Convergence Protocol* – a control protocol for data streams via the mobile network's radio interface
PLMN	*Public Land Mobile Network* – the terrestrial part of a mobile communications network providing a public service
PPDR	*Public Protection and Disaster Relief* – a collective term for crisis response units
QAM	*Quadrature Amplitude Modulation* – a term for modulation with a greater number of phase-amplitude states
QoS	*Quality of Service* – a set of metrics used to express transmission quality
QPSK	*Quadrature Phase Shift Keying* – a type of modulation of a digital signal onto an analogue carrier with 4 states
RAN	*Radio Access Network* – a radio access network
RFID	*Radio Frequency IDentification* – a specialised communication method for radio identification using minimal resources
RLC	*Radio Link Control* – control of a mobile network radio link to the MT at the physical layer,
RMR	*Railway Mobile Radio* – a collective term for frequency bands allocated by ECC recommendations for railway use in Europe
RRB	*Radio Resource Block* – a logical unit for organising signals on the mobile network's radio interface
RRH	*Remote Radio Head* – a component of mobile network architecture that remotely implements the physical transmission layer for a base station

SIM	*Subscriber Identity Module* – an electronic device that securely stores the identification data of a mobile communications service user
SINR	*Signal-to-Interference-and-Noise Ratio* – the ratio of the signal to noise and interfering signals
SNR	*Signal-to-Noise Ratio* – the ratio of the signal to noise
SPOŽES	Compendium for the valuation of railway structures – methodology for valuation at the feasibility study stage, drawn up by the SFDI
SRCC	*Smart Rail Connectivity Campus* – a centre for research, development and testing of innovations for the railway sector, based in Annaberg-Buchholz, Saxony
SRS	*System Requirement Specifications* – a UIC document describing the use of the FRMCS function, forming part of the annexes to the CCS TSI
SS-RSRP	*Secondary Synchronisation Reference Signal Receive Power* – a measure of the received signal strength prior to demodulation and decoding, measured on the synchronisation component of the radio signal in 4G/5G networks
SVOD	Association of Passenger Rail Operators
SW	*software* – the software components of an information and communications system
TC RT	*Technical Committee Rail Telecommunications* – the ETSI committee responsible for railway telecommunications
TCMS	*Train Control and Management System* – a system for controlling and managing on-board technologies (referring to auxiliary technologies; in the case of traction, only in a manner that does not affect the train's movement)
TDD	*Time Division Duplex* – a method of dividing the transmission direction using time division multiplexing within the same frequency band
TETRA	designation of a narrowband digital radio communication system for emergency services in accordance with the ETSI EN 300 392 series standard
TSI CCS	*Technical Specifications for Interoperability relating to the Control-Command and Signalling subsystems of the rail system in the European Union* – a general term for the EC Regulation laying down rules for the interoperability of control-command and signalling subsystems of the rail system in the European Union
UAS	*Unmanned Aircraft System* – unmanned aircraft
UIC	*Union Internationale des Chemins de fer,* International Union of Railways – an organisation bringing together countries to coordinate the development and operation of rail transport
UL	i – the direction from the mobile terminal to the network
UMTS	*Universal Mobile Telecommunications System* – a general term for third-generation mobile network technologies
UNIFE	*Union des Industries Ferroviaires Européennes* – an interest group representing the European railway industry
URS	*User Requirements Specification* – a UIC document [35] describing the use of FRMCS communications from a user's perspective
VLEO	*Very Low Earth Orbit* – a system of satellites orbiting at very low altitude
VRT	high-speed line
WG	*Workgroup* – working group
WiFi	a collective term for specific technologies and a range of WLAN standards; originally a trade name for products implementing the standard
WLAN	*Wireless LAN* – a LAN operating via a radio interface
ŽESNAD	Association of Railway Freight Operators of the Czech Republic, z.s.

1 Applications to support railway operations

1.1 FRMCS applications used in the Czech Republic

The publicly discussed strategic plans for the development of rail transport in the Czech Republic do not currently contain any specific strategy regarding the deployment of FRMCS – the successor to the GSM-R system as the communication component of ERTMS – nor its relationship to applications; this is not included in the current Strategic Document: National ERTMS Implementation Plan [26], not even in its latest version from 2024

- The formal chapter on FRMCS merely states that its deployment cannot be planned responsibly, as its technical specifications have not been finalised and no suitable products are available on the market;
- It does not address applications supporting railway operations, with the exception of ETCS – the train control application. Furthermore, the term ‘application’ is used differently in FRMCS standards than in standard ICT practice, tending to mean ‘a communication function serving applications’. Through this mechanism, the applications themselves are classified into groups according to their purpose, on the assumption that their individual implementations will, in principle, have similar communication requirements.

Views on this concept of a set of applications, and the subset of these to be supported during the transition phase (migration) from GSM-R to FRMCS, have evolved as the FRMCS standards have been developed. Table 1 summarises the various perspectives on the importance of critical communication applications; the individual columns indicate the source of the assessment:

- **Applications according to UIC URS** refer to the definition of applications in Annex 1 of this study
- **Support in GSM-R** represents the basic set of applications supported in the current EIRENE ERTMS system (GSM-R plus ETCS, now including ATO up to GoA2). Support for all these applications is a fundamental prerequisite for migration. Support for ATO is, however, dependent on the GSM-R packet service (PS), which is not yet in operation in some countries.
- **Report 74** reflects the perspective as of 2020 and specifies the phase in which [5] includes the required capacity within the FRMCS requirements (Migr is the migration phase with parallel support for both FRMCS and GSM-R; Target is the target state following the decommissioning of GSM-R, which refers to an even earlier UIC document from 2018). It adds, from the perspective of the time, operationally promising applications such as Emergency Calls to the public network, remote control of high-voltage systems, critical video, and supporting train localisation applications – all of which are necessary for the functioning of voice applications in particular – to the set of requirements already designated for the migration period. The set also included On-board Intelligence and Sensors – a group of applications which, as development progressed, broke down into smaller units and has practically disappeared from the UIC definitions.
- **FRMCS planning** outlines support plans for individual applications within the FRMCS V2 and V3 standards, based on selected planning documents (specifically [27] and the most recent plan compiled to date, which forms part of Chapter 9.2 of the draft version [28] of V1.1). These were created following the publication of the CCS TSI 2023, which represents the FRMCS V1 specification, intended for its legalisation in a pilot deployment. V2 represents the applications forming the basis of interoperability and is therefore intended for operational testing within the MORANE 2 programme. Together with the applications included in V3, they form a set intended for the CCS TSI 2027 (FRMCS Baseline 1), which will be sufficiently comprehensive to enable the manufacture, procurement and installation of FRMCS components on rolling stock and infrastructure – a prerequisite for migration. Approximately one-third of the applications do not yet have defined or functional requirements within the FRMCS framework and will only be subject to standardisation in V4 and later versions. Their implementation may require an additional upgrade of the FRMCS equipment installed during the migration.
- **The survey in the Czech Republic** reflects the views gathered in a questionnaire submitted to participants in the working group preparing this study – two freight operators of different sizes, a smaller passenger transport operator, and SŽ as the representative of the infrastructure manager. Interest in the applications is assessed in a similar way to the respondents’ motivation in the chapter, on a scale from 0 (irrelevant) to 5 (crucial for operations). For transport operators, the average rating is given; values in brackets are not statistically significant due to the wide variation in ratings. The differences are then commented on in detail in the following text.

Table 1 – Communication for critical applications within the UIC URS framework

Applications according to UIC URS		Support in GSM-R	Report 74	FRMCS planning	Survey	
					Operators	IM
5.1	Outgoing voice communication on the train from the train driver to the dispatcher responsible for the train	yes	Migr	V2-V3	5.0	5
5.2	Incoming voice communication on the train from the dispatcher to the train driver	yes	Migr	V2-V3	5.0	5
5.3	Voice communication between train drivers on different trains, or with ground staff	yes	Migr	V2-V3	5.0	5
5.4	Voice communication during shunting	yes	Migr	V2-V3	5.0	5
5.5	Track maintenance voice communication				(2.3)	4
5.6	Voice communication for shunting	yes	Destination	(V2) V3	5.0	5
5.7	Public emergency calls		Migr	not defined	5.0	4
5.8	Voice communication for ground staff			--	3.7	5
5.9	Communications for Automatic Train Protection (ATP) (ETCS)	Yes	Migr	V2	5.0	5
5.10	Automatic Train Operation (ATO) communication	PS	Migration/Target	V2-V3	4.3	5
5.11	Data communication for managing track closure works			not defined	(2.3)	3
5.12	Track maintenance warning system communication			not defined	(3,3)	5
5.13	Locomotive remote control communications		Migr	not defined V2-V3	5.0	2
5.14	Monitoring and control of critical infrastructure			--	(2.7)	4
5.15	Railway emergency communications	yes	Migr	V2	5.0	5
5.16	Communication between the on-board safety device and the ground-based system		Objective	V3	5.0	0
5.17	Public emergency communication with the train			not defined	3.0	1
5.18	Lone worker			not defined	(2.7)	4
5.19	Voice recording and access to recorded data			--	5.0	5
5.20	Data recording and access to recordings			--	5.0	4
5.21	Data communication for shunting			--	4.0	0
5.22	Data communication for train integrity monitoring		Objective	V3	4.3	0
5.23	Public emergency alert		Migr	V2-V3	4.3	4
5.24	Outgoing voice communication from train crew to ground-based users			not defined	(2.7)	0
5.25	Incoming voice communication from ground users to train crew			not defined	(2.7)	0

Application in accordance with UIC URS		Support in GSM-R	Report 74	FRMCS planning	Survey	
					Operators	IM
5.26	Emergency communication for railway staff			not defined	5.0	5
5.27	Critical live video		Migr	V2-V3	(3.7)	0
5.28	Early warning system – safety-related		Objective	V2-V3	4.7	5
5.29	Data communication for virtual hanging		Objective	V3	3.3	0
5.30	Securing decoupled trainsets			not defined	4.7	0

For applications already in operation – voice, emergency communications and train control, as well as data recording and access (5.27) – there is consensus amongst all participants on the high importance of such applications. In other cases, assessments differ for various reasons; however, each application is of at least moderate importance to one of the participants:

- Seven applications are **relevant only to transport operators**, who have given them a high rating, whilst the IM has designated them as irrelevant to itself (0).
- For five applications – Monitoring and Control of Critical Infrastructure (5.14), Ground Staff Voice Communications (5.8), Lone Worker (5.18), Track Maintenance Voice Communications (5.5) and Track Maintenance Warning System Communications (5.12) – the situation is the opposite: they are **of little relevance to transport operators** but are highly rated by the IM. Furthermore, for the last three, **which relate to track maintenance**, there is a wide divergence of views amongst transport operators. On the one hand, they generally recognise its importance for staff safety; on the other hand, they are concerned that train drivers might be held liable for this safety and indicate that such communication is not the responsibility of the transport operator.
- There are also significant differences in transport operators' views on **Data communication for managing track closure works** (5.11) and **Voice communication between train crew and ground-based users** (5.24 and 5.25). The use of such communication by transport operators is rare (e.g. only for work trains) or non-existent (freight transport without train crew); however, as in the previous case, its usefulness for other railway services is generally recognised (rating 3–4). IM expresses interest only in the former.
- A similar view is taken of **Critical Video** (5.27), which is likewise the largest expected consumer of transmission capacity and is unavailable in frequency bands below 2 GHz (see Chapter 2.6). The view on general usefulness among transport operators is thus compounded by the unjustifiable costs of both the communication and IT infrastructure; IM sees no use for it whatsoever.

As with the previous section, Table 2 summarises the views on the importance of non-critical applications, classified by FRMCS standards as 'performance' applications. These applications are intended for operational use and aim to increase the efficiency of railway operations. In the FRMCS standards, these applications are generally also classified as **non-interoperable**, in the sense that they are used by the vehicle operator (or, where applicable, the owner or manufacturer) for internal purposes; they are not accessible to other entities and therefore **need not be** interoperable in a technical sense. The communication scheme for such applications differs from that of interoperable applications – the vehicle connects from all FRMCS domains to its home domain (the country of registration or the registered office of the using entity).

None of these applications are supported within GSM-R; they are operated under commercial terms on MNO networks. The meaning of the other columns is the same as in Table 1. Most applications do not yet have defined or functional requirements within the FRMCS framework; they will be subject to standardisation only in V4 and higher versions.

Table 2 – Communications for performance applications within the UIC URS framework

Applications according to UIC URS		Report 74	Planning FRMCS	Survey	
				Carriers	IM
6.3	Voice communication between train drivers of multiple trains, excluding ground-based users	--	not defined	5.0	0
6.4	Voice communication on the train	--	Not defined	4.0	0
6.5	Track-side telephony	--	not defined	3.0	5
6.6	Voice announcements on the train to passengers (train public address system)	--	--	(3.3)	0
6.7	Station announcement	--	undefined	2.3	2

Application in accordance with UIC URS		Report 74	Planning FRMCS	Survey carriers	Survey IM
6.8	Communication in stations and service facilities	--	not defined	4.3	4
6.9	Train telemetry communication	Target	V2-V3	5.0	5
6.10	Infrastructure telemetry communications	--	not defined	(3.3)	5
6.11	Remote control of on-board equipment	Target	not defined V2-V3	5.0	0
6.12	Monitoring and control of non-critical infrastructure	--	not defined	(2.7)	4
6.13	Non-critical live video	--	undefined	3.8	2
6.14	Wireless data communication for train crew	--	not defined	4.0	0
6.15	Wireless data communication for railway staff on platforms	--	not defined	(2.7)	5
6.17	Help for the train driver – train performance	--	undefined	4.3	2
6.18	Data communication for train departures	--	not defined	5.0	0
6.19	Messaging services	--	--	5.0	5
6.20	Data transfer	--	--	5.0	5
6.21	Recording and broadcasting of information	--	not defined	5.0	5
6.22	Transfer of CCTV archives	--	undefined	(3.3)	0
6.23	Live video call	--	undefined	(2.7)	3
6.24	Augmented reality information transfer	--	undefined	3.3	0
6.25	Real-time speech translation	--	undefined	4.3	4

The differences in the ratings are similar to those for critical applications:

- Eight applications are again **relevant only to transport operators**, though not all are of key importance to them. Voice communication on board the train directed at passengers (train public address system) (6.6) is relevant only to passenger transport operators, although some freight transport operators also rated it as (generally) useful.
- **The transfer of CCTV archives** (6.22) is assessed in a similar way; however, some freight carriers consider the resulting data volumes (see example below) to be too large for systematic centralised archiving, as they do not justify the costs of the necessary IT resources, and therefore prefer selective off-line transfers. Opinions are similarly divided on **the transmission of augmented reality information** (6.24), which some respondents are unable to integrate into their processes.
- Four applications – Line-side Telephony (6.5), Infrastructure Telemetry Communications (6.10), Monitoring and Control of Non-Critical Infrastructure (6.12) and Wireless Data Communications for Railway Staff on Platforms (6.15) – are again **of little relevance to carriers**, but are highly rated by infrastructure managers. The divergence in transport operators' views is once again due to the gap between the generally recognised importance of these applications and their actual irrelevance to freight operators.
- Interest in **live video** (applications 6.13 and 6.23) is consistently low (and lowest amongst IMs); as with critical applications, this is expected to be the largest consumer of bandwidth, requiring communication in 5G frequency bands above 2 GHz, with significant implications for the necessary ground-based infrastructure for such communication.
- Conversely, interest in **real-time speech translation** (application 6.25) is surprisingly high across the board, as it addresses real-world problems in the ever-expanding cross-border transport of both freight and passengers, where the proposed alternative measure is the (likely highly unpopular) proposal to introduce a single pan-European transport language.

There is **consensus on the high importance**, shared by both transport operators and infrastructure managers, of applications which, due to their general significance, are already in widespread use – Train Telemetry (6.9), Messaging Services (6.19), Data Transmission (6.20) and Recording and Broadcasting of Information (6.21). The first of these also includes the measurement of high-voltage electrical consumption, as required by the TSI; this is one of the few non-critical applications that is also operated on GSM-R.

At present, all **video applications** are considered to place extreme demands **on the system**. An illustrative example is a specific system for recording the situation around a locomotive, which was discussed during a survey with one of the freight operators. In this system, footage is continuously recorded using up to four HD cameras mounted on the locomotive, representing a continuous data stream of 4 MB/s – significantly higher than the

the anticipated capacity available in the FRMCS within the RMR bands (see Section 2.6). For real-time situation overviews, therefore, only 1-second samples of the recording are and will continue to be transmitted. The complete local recording amounts to 20–40 GB per day on each vehicle, i.e. 2–4 TB of data per day for the entire HV fleet. However, only a fraction of this volume is actually used for incident resolution – 50 five-minute recordings totalling 15 GB, i.e. 0.4–0.7 per cent. Transferring a single recording within a still-acceptable timeframe of 20 minutes requires a speed of 2 Mb/s or higher from any point along the line.

The UIC's classification of applications currently also includes four business **applications**, representing wireless access for staff and passengers in various areas of the railway. These applications **are not the subject** of this study.

1.2 Proposals for changes to standards

During discussions on the definitions of application groups according to the FRMCS URS, it became apparent that there is no generally accepted Czech equivalent within the sector. There are several reasons for this:

- The FRMCS URS document itself was not included as an annex to the published CCS TSI 2023 (EC Regulation 2023/1695), so it has not been officially translated. Furthermore, in the case of other documents that have been translated within the framework of the TSIs (and other pan-European railway regulations), it appears that the translations provided by the European Commission and the European Parliament as part of the legislative process do not adhere to established Czech railway terminology.
- Officially available glossaries of transport terminology, including railway terminology, do not reflect current developments in the sector, as they have not been updated in the last 10 years – the national Dictionary of Transport Terminology [33] was published in 2010, whilst the UIC RailLexic [34] was last updated to version 4.0 in 2011.
- The brief definitions of applications in the FRMCS URS also deviate significantly in substance from railway practice in the Czech Republic and, most likely, from practice in other countries as well, as they fail to distinguish terminologically between certain fundamental operational phenomena and categories. Examples of this include the use of the single term 'train' to refer to both a train and a multiple unit, the term 'driver' without any qualifiers – from which, or even from its context in the definitions, it is impossible to distinguish whether it refers to the driver in charge of a high-speed train or the crew operating other high-speed units coupled to the train – and the narrowing of the concept of 'banking' ("banking") solely to the less frequently used unhitched pushing method, or the term "controller", which does not distinguish between the individual operational roles of dispatchers/traffic controllers.

During discussions within the study's working group, a Czech translation and an associated English-Czech explanatory glossary of the terms used, which the working group proposes to submit to the European Commission's Translation Service in Luxembourg as a standard for the translation of railway legislation texts from these bodies into Czech, e.g. via the Ministry of Transport's Department 130 and the transport attaché at the Permanent Representation of the Czech Republic to the European Commission. The translation of the FRMCS URS definitions and the glossary are contained in Annex 1 of the study.

2 FRMCS system coverage

According to [8], FRMCS (5G NR) **signal coverage** is more complex than in the case of GSM-R. Unlike GSM-R, it cannot be expressed using a signal strength threshold, as transmission quality is influenced by many factors, such as dynamically selected modulation schemes, various MIMO schemes, the TDD multiplexing ratio (for the 1900 MHz band), link adaptation mechanisms, and functional blocks that are not fully standardised, such as the scheduler, amongst others. Signal quality at a specific location is therefore determined by several parameters – RSRP, RSRQ and SINR – which are calculated using multiple reference signals. As neighbouring cells may transmit on the same frequencies (radio resource block, RRB), in many cases the limiting factor is interference between the cell's own signal and signals (both gNB and MT) from neighbouring cells. The ultimate indicator from the user's perspective is the achievable data rate, which varies between the uplink (UL) and the downlink (DL) to the MT, and the decisive signal parameter for determining this is the signal-to-interference-plus-noise ratio (SINR).

The following factors are decisive for **band selection**:

- achievable communication speed,
- any need to increase gNB density (reducing cell sizes) compared with the existing GSM-R infrastructure in the 900 MHz band (n100), influenced by various frequency-dependent propagation characteristics, such as antenna directional characteristics, multipath propagation modes and induced interference;
- interference with neighbouring (other) bands in use and measures to mitigate it.

A critical point of mutual interference in all the bands under discussion is **the interference between antennas** located within the relatively small space of a vehicle's roof. RMR bands do not significantly interfere with one another; however, this applies only if at least basic isolation conditions are met, as determined by the arrangement of the individual antennas on the vehicle's roof. However, ensuring these conditions is not straightforward given the large number of antennas both in the system being replaced (a typical GSM-R configuration with 1x on-board voice MT and two EDORs for ETCS) and in the new system (simulations [3] with 1x4 and 4x2 MIMO configurations, i.e. at least 2 antennas on the vehicle). Furthermore, the attenuation provided by the spatial arrangement is usually insufficient; possible measures according to [29], for example, assume an antenna spacing of only 2 m, and achieving the necessary suppression of unwanted signals relies on the insertion of combiner filters between the shared FRMCS broadband antennas and the radio modules for the individual bands. However, with more extensive use of filters, there is a concern [6] regarding the high cost and also the weight of the components installed on the vehicle. The antennas and their feed lines for GSM-R always remain separate.

2.1 Use of the 900 MHz band

The RMR band for the exclusive use of railway communications, commonly referred *to as* '900 MHz' – or, more precisely, n100 according to CEPT – is a dual band (for FDD operation) in the ranges 874.4–880.0 MHz and 919.4–925.0 MHz, extended by 2 × 1.6 MHz compared to the original GSM-R band (876.0–880.0 MHz and 921.0–925.0 MHz) by 2 × 1.6 MHz. The anticipated possibility of a national extension of up to 3 MHz (to 873–880 and 918–925 MHz) is not currently relevant for the Czech Republic. The extended band is expected to be utilised in accordance with [5]:

- during the migration, in parallel for the existing GSM-R system and its successor, the FRMCS; the possible approaches are discussed in section 2.1.3;
- with the aim of using NG technology broadband channels of up to 5 MHz, possibly supplemented by several 200 kHz NB-IoT channels, operated under the conditions set out in ECC Report 318, intended, for example, for radio communication between infrastructure elements or a track maintenance warning system.

For the use of the n100 band with wideband modulations, the CEPT report [4] sets out the following conditions in the form of a transmitted spectrum mask for both transmission directions, which do not require further coordination with services in adjacent bands:

- The permitted (equivalent isotropically radiated power, EIRP) transmission power for the BS (referred to as gNB in 5G terminology) in the new band extension, to protect operations in the 880 – 915 MHz, to protect traffic in the 880–915 MHz band (a wideband transmitter operates at the same power across the entire band used, so the transmit power is limited by the lower edge of the band in use). At national level, it is possible to authorise higher power levels provided they do not cause interference with other services in the band up to 915 MHz, or, conversely, to further limit the transmit power to 65 dBm regardless of the bandwidth and channel position within the n100 band.
- For coordination at network boundaries, Recommendation ECC (08)02 specifies specific maximum signal levels for neighbouring networks at and near the boundary (59 and 41 dBuV/m respectively, i.e. below –66 dBm).

- The permitted EIRP for vehicle-mounted MTs is 23 to 31 dBm with an adjacent channel leakage ratio (ACLR) of at least 37 dB, and the emission mask complies with 3GPP requirements for LTE/NR; for handheld terminals, the permitted EIRP is only 23 dBm with an ACLR of 30 dB. In both cases, the MT must have functional and activated transmit power control.

2.1.1 Signal propagation conditions

According to [7], unlike GSM-R, FRMCS does not exhibit the same coverage in both transmission directions; coverage is essentially determined by the conditions for the uplink (UL), even at increased MT transmitter power (31 dBm, i.e. less than 39 dBm for GSM-R, and with a significantly wider bandwidth). This more complex transmission method is more sensitive to conditions at the edge of the coverage area (cells), where merely maintaining the minimum RF signal level, as with GSM-R, is no longer sufficient. Nevertheless, the coverage of GSM-R and FRMCS systems in the 900 MHz band is considered to be approximately the same.

At ETSI, relatively extensive propagation simulations were carried out using several different simulation tools, the results of which are summarised in [3]. Each of the three tools used proved more suitable for modelling different aspects of transmission – whilst two models allowed simulation under various MIMO configurations (with quite different results in terms of data rate), the third model was able to model the influence of different spectrum allocations to neighbouring cells (reuse factor) and vehicle speed (Doppler effect).

The modelling reveals the following conditions for the 900 MHz band:

- In both urban environments and open countryside, the parameters of the uplink (UL) are significantly influenced by transmit power, meaning that only MTs with a transmit power of 31 dBm are practically viable. For downlink (DL) simulations in both environments, the modelling also revealed a significant anomaly in behaviour near the base station (gNB), where, due to interference from the back lobes of antennas on the opposite side of the same mast and the high directivity of MIMO transmissions, the (practically within 300 m of) the BS (gNB), both SINR and data rate drop to values close to those at the cell edge in open terrain (at a distance of 1–2 km).
- Uplink transmission conditions in urban environments are worse than in open country, even though the cells are planned to be only half the size. The SINR at the gNB receiving antennas drops below 2 dB for half the MT at the cell edge (below 7 dB in open country). As expected, this is due to a higher proportion of NLoS propagation and greater LoS attenuation (lower antennas and denser built-up areas).
- Modelling revealed a clear optimum in the MIMO configurations investigated, ranging from 1×2 to 2×4 (and, in exceptional cases, 4×4). The best results for uplink parameters were achieved by the 2x4 configuration (with better interference suppression, directivity and gains from spatial multiplexing and the effective area of the receiving antenna); however, their use is currently impractical, as even the Rel18 standards permit only one transmit antenna per MT. The 4x2 configuration also performs well for the downlink (although installing four antennas on a vehicle would further improve the ratio, this is not feasible for space reasons). Simulations yield the same results regarding MIMO for both open countryside and urban environments.
- The configured (fixed) frequency allocation between neighbouring cells (Frequency Reuse), which aims to limit interference at the cell edge at the cost of reduced speeds at its centre, did not yield clear-cut results, and the study recommended leaving frequency organisation to the automatic mechanisms of 5G NR.

A good illustrative example of the differing reception conditions for GSM-R and FRMCS is **the result of preliminary planning** for the vicinity of Thionville railway station Thionville (FR), as reported in [8], operating in the 900 MHz band with a cell diameter of up to 8 km in flat countryside with suburban development, masts approximately 23 m high and a base station antenna gain of 17 dBi:

- The results of the comparative GSM-R planning showed a signal level of –95 dBm at the edge of such a cell, meeting the EIRENE standards.
- The signal level for FRMCS (SS-RSRP) at the same location was –115 dBm and the SINR was around 0 dB. Under such conditions (at the boundary between the use of QPSK and 16QAM modulation), the theoretically achievable data rate is, according to both [8] and [3], around 2 Mb/s; in the specific case cited, the radio planning predicted a minimum of 480 kb/s (both downlink with 2×2 MIMO diversity and uplink).

2.1.2 Interference with neighbouring bands

For the 900 MHz RMR band (n100) [5], potential mutual interference with the following radio communication bands is addressed:

- BS reception (uplink) for networks in the band up to 915 MHz is protected by adjusting the mask of permitted transmission powers in accordance with paragraph 2.1 (by reducing the power of channels extending below 921 MHz). Conversely, vehicle stations (generally MT) of the FRMCS system must be sufficiently immune to transmitters from networks in this band.
- Vehicle stations (generally MTs) of the FRMCS system must also be sufficiently immune to network transmitters in the band above 925 MHz; this requirement is already met by GSM-R receivers designed in accordance with ETSI TS 102 933-1, most of whose requirements will also apply to FRMCS.
- Furthermore, FRMCS on-board units (generally MT) must also be sufficiently immune to short-range transmitters (RFID or data transmission, Wi-Fi 802.11ah) operating in the 915.0–919.4 MHz band, which will be ensured by meeting the requirements set out in ECC Report 313, which are mandatory for FRMCS receivers.

- Similarly, BS receivers (gNB, uplink) must, according to ECC Report 313, be immune to short-range (data) transmitters operating in the 874.0–874.4 MHz band; spectrum harmonisation for this case is provided by EU Regulation 2022/180 and ERC Recommendation 70-03 of June 2019, which have already been implemented in the Czech Republic.

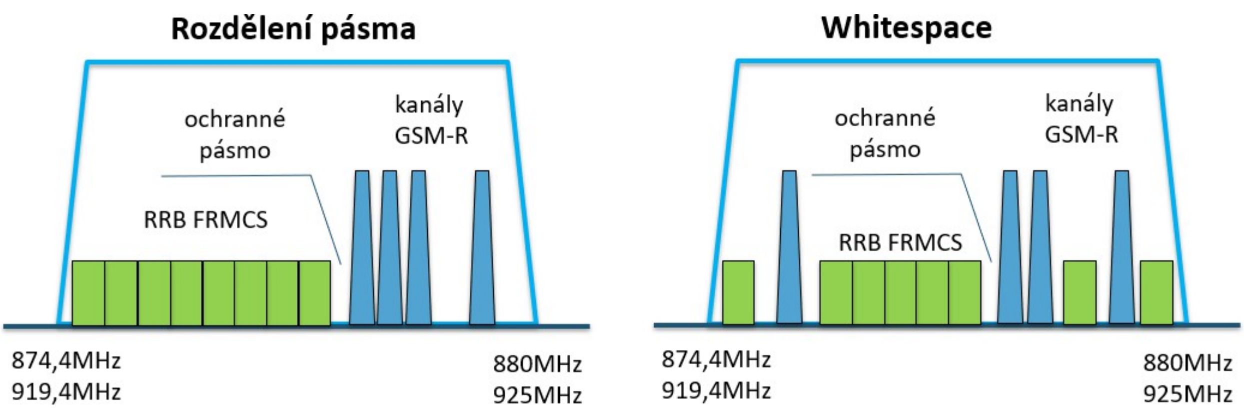
2.1.3 Coexistence of GSM-R and 5G/FRMCS in the band

The original intended use, as cited in [5], would have allowed a full-fledged LTE channel with a bandwidth of 1.4 MHz to be operated in the new extension, including a 0.1 MHz spacing from the existing band for GSM-R. The UIC's decision to use only 5G technology for European implementations precludes such coexistence, as the minimum 5G channel bandwidth is higher according to current 3GPP standards.

Under these conditions, the scenario involving the simultaneous use of the 900 MHz band for both systems has two basic variants [7]:

- frequency division of the band into a section reserved for GSM-R operation (taking into account interference with various neighbouring bands, a contiguous allocation at the upper end of both paired bands) and FRMCS (the remainder at the lower end of the bands, including a new 1.6 MHz extension)
- overlapping operation of both systems within the same band, whereby, thanks to advanced 5G NR modulation techniques, it is possible to utilise even non-contiguous sections of the band at specific locations not occupied by GSM-R traffic (so-called 'whitespace').

Figure 1 – Options for sharing the 900 MHz band



The division of the band into contiguous sections for GSM-R and FRMCS has the following limitations and operational implications:

- The spectrum allocation for FRMCS is limited by the bandwidth that must be reserved for GSM-R operations. The usual outcome of radio planning is a requirement for at least 10 channels (on a secondary line with low traffic), but typically 12–14 channels (on a line with normal traffic), taking into account a 2 × 100 kHz separation band, i.e. at least 2.2 MHz; however, in the past, most network operators utilised all 19 original channels – i.e. 4 MHz – in their planning.
- For FRMCS operation, this leaves the 1.4–3.2 MHz band (maximum 15 RRBs), which is narrower than the 5 MHz supported by 5G NR standards. To operate in narrower bands, amendments to the 3GPP standards are required, on which 3GPP WG4 (network infrastructure) and WG5 (terminal) have been working. The result is the definition of a new modulation scheme for the 3 MHz channel in the Rel18 specification.
- In most networks, such a division will require a re-planning of the GSM-R radio system, which is highly likely to trigger coverage measurement campaigns and the need for re-approval, including of the ETCS application deployed on GSM-R; these will entail additional costs and time delays and create bottlenecks, for example due to a shortage of qualified personnel. Nevertheless, the scenario anticipates changes throughout the migration period, during which the allocation for GSM-R will be gradually reduced as traffic volumes shift to FRMCS. However, it is not possible to estimate the precise course of this transition, as the conditions for the coexistence of GSM-R and FRMCS under the current CCS TSI 2023 allow users to split traffic between the two networks (e.g. ATP/ETCS on FRMCS, whilst keeping the voice service on GSM-R).

An overlapping sharing method (whitespace) is being developed within ETSI TC RT as an initiative by Kontron. Under this method, the FRMCS system

- utilises a 5 MHz bandwidth allocation at the lower edge of the n100 band; however, this allocation is not contiguous, as local gNB configurations exclude channels used by the co-located GSM-R BS, including the necessary guard bands. The feasibility of such a deployment has so far been confirmed by ETSI TC RT through tests on 4G LTE technology; however, confirmation is also expected for standard 5G NR R17 modulation techniques, specifically in tests as part of the 5G-RACOM project, scheduled to run until 2025.

- Minimal interference between the two systems can be achieved if the signal strength of both is comparable at every point within the coverage area. This implies the need for co-location of the gNB FRMCS and the GSM-R BS, with both transmitters operating at approximately the same EIRP.

The table summarises the main differences between the two coexistence options:

Table 3 – Main differences in the proposed methods of 900 MHz band sharing

Band allocation	Overlapping sharing (whitespace)
For FRMCS, a narrow channel (RB) of max. 3.2 MHz	For FRMCS: full channel (RB) 5 MHz
Requires 5G NR Rel18	5G NR Rel17 is sufficient
EIRP determined on the basis of 3GPP work	EIRP within narrow limits equivalent to GSM-R
Contiguous spectrum allocations for FRMCS and GSM-R	Overlap; FRMCS band is non-contiguous
gNB configuration handled on a site-by-site basis	Configuration of each gNB is individual

2.2 Use of the 1900 MHz band

The RMR band, commonly referred to as 1900 MHz TDD, or more precisely as n101 according to CEPT, is a band newly allocated from 2021 for the exclusive use of railway communications. The band has not yet been allocated for railway radio communications in the Czech Republic; the entire 1900–1920 MHz band is **currently allocated** in the Czech Republic **for the mobile service, short-term or experimental use, and** will be allocated for railway radio communications from 2025, when the IM may apply for it on the basis of a strategic and economic assessment**.**

The main distinguishing feature of the band is the use of time division duplex (TDD), which has specific limitations and operational implications not only for the migration phase but for the entire period of use of this band:

- Neighbouring network cells require mutual synchronisation (time and frame) to prevent interference, including between neighbouring cells of different networks. Synchronisation also involves adjusting the duplex ratios (schemes) of neighbouring cells, or conversely, completely isolating cells in the event of a fundamental change to the duplex scheme, which limits the otherwise high flexibility of capacity allocation between the uplink and downlink.

- Coverage (range) is reduced due to the significantly higher frequency and requires a higher density of gNB sites compared with the 900 MHz band (i.e. compared with the existing GSM-R system). Radio planning in this band will also be more complex, as – just as with the 900 MHz band – it is no longer based on receive level limits, but involves the selection of the MT's transmit power. The densification of gNBs is therefore not comprehensive, but applies only to existing cells with a high ISD (i.e. cells in open countryside with a low current traffic load). The conditions are discussed in more detail in Section 2.2.1.

In addition to the widespread deployment of FRMCS in the 1900 MHz band (where the 900 MHz band cannot be used), selective deployment to meet specific needs offers significant benefits, leading to various hybrid scenarios, e.g. [7]:

- increased capacity in areas of higher demand, such as large marshalling yards and railway junctions, dense urban networks or geomorphologically complex areas with an increased need for coverage. Such a situation often arises at major junctions connecting individual lines operated in the 900 MHz band (e.g. for ETCS L2), where coverage can be provided independently in the 1900 MHz band, or possibly in overlap with FRMCS also deployed in the 900 MHz band;

- at the boundary between this network and a network that still uses the 900 MHz band for GSM-R without the possibility of coordinating usage as set out in Section 2.1.3. In such cases, to prevent interference, the border sections may be covered in the 1900 MHz band.

For the sake of completeness, it should be noted that there are also situations where, conversely, coverage of a 1900 MHz network is required through installations in the 900 MHz band, such as areas with insufficient coverage due to the impossibility of adding passive infrastructure (masts) or the coverage of tunnels using various repeater-based technologies that are unable to transmit signals in this band or ensure the necessary synchronisation for TDD.

For the use of the n101 band, the CEPT report [4] sets out the following conditions in the form of a transmitted spectrum mask for both transmission directions:

- The permitted (equivalent isotropically radiated power, EIRP) transmit power for a BS (referred to as a gNB in 5G terminology) without coordination with other networks is up to 65 dBm for a 10 MHz channel width; nationally, it is theoretically possible to permit higher power levels, but only subject to coordination with the networks concerned.

- Where specific coordination at network boundaries is not possible, ECC Report 353 and the related ECC Recommendation 23-01 specify the default TDD frame structure and field strength at the boundary.
- The permitted EIRP for vehicle-mounted terminals is up to 31 dBm with adjacent channel leakage ratio (ACLR) of at least 37 dB; for handheld terminals, the figures are 23 dBm and 30 dB respectively. In both cases, the terminals must have functional and activated transmit power control.

The following factors are decisive for the overall impact of introducing the 1900 MHz band:

- the achievable communication speed in this TDD band is determined not only by the allocated bandwidth and achievable SINR, but also by the set RRB UL/DL ratio (unlike MNO networks, where this is typically set in favour of the uplink at ratios ranging from 50:50 to 90:10), overlap of the utilised band in neighbouring cells (statically configured or dynamically applied only at the coverage boundary), the MIMO scheme (with varying effects in the UL and DL) and others;
- if both neighbouring networks opt to use the 1900 MHz band, they must also address mutual time synchronisation and coordinate TDD duplex schemes to prevent interference in border areas. The procedures for such coordination are set out in more detail in documents published by the UIC UGFA;
- it is necessary to increase gNB density (reduce cell sizes) by a certain ratio compared with the 900 MHz band (n100), although this is not directly determined by the frequency ratio.

2.2.1 Signal propagation conditions

Modelling using three different simulation tools, as for the 900 MHz band (see 2.1.2), [3] reveals the following conditions for the 1900 MHz band:

- The effect of MIMO configurations, investigated in the range from 1x2 to 2x8, proved to be contradictory. The most complex configurations, with 8-port antennas on the gNB, showed only minimal benefits for uplink (UL) parameters, whilst for downlink (DL) they were clearly counterproductive (the higher directivity of the transmit antenna, due to the EIRP limit, restricts the total transmit power). Simulations for both open terrain and urban environments yield the same results regarding MIMO. In the 1900 MHz band, which uses TDD, the outdoor configuration for UL and DL cannot be separated; therefore, its selection will be a compromise requiring further research and testing.
- Compared with the n100 band (900 MHz), simulations showed significantly lower (by 5 dB) attenuation at the cell edge in open terrain (due to predominantly NLoS propagation) and higher antenna gain at 1900 MHz.
- The uplink has significantly poorer performance in urban environments, heavily influenced by transmit power; consequently, only MTs with a transmit power of 31 dBm are practically viable. A similar situation applies to the downlink for large cells in open terrain (in the simulation with a radius of 8 km), where gNB transmission at the maximum permitted power of 63 dBm EIRP is essential.
- In most simulated scenarios, interference at the cell edge was the limiting factor, so the interference mitigation functions implemented in 5G technology are crucial for operation. However, static frequency allocation between pairs (or triplets) of neighbouring cells limits the data rate across the entire cell, so here too it was confirmed that the use of dynamic techniques is more appropriate.
- In the simulations, the 1900 MHz band proved to be more sensitive to MT movement (the Doppler effect) than the 900 MHz band.

A telling example of FRMCS transmission conditions is, once again, the result of preliminary planning for the area around Thionville railway station (FR), as reported in [8]. The FRMCS signal level (SS-RSRP) at cell boundaries for this band was as low as -120 dBm, and the SINR was as low as -5 dB in some places. Even under such conditions, the downlink (DL) transmission rate remained at a minimum of 480 kb/s thanks to diversity (2x2 MIMO), whilst the uplink rate fell below 70 kb/s in some locations. Here too, the planning results confirmed the generally accepted rule that, when transitioning to the 1900 MHz band, it will be necessary to increase the density of base stations (gNB), i.e. to reduce the ISD of cells, and that FRMCS transmission is critical, particularly for uplink conditions.

An indication of the fulfilment of coverage requirements in the 1900 MHz band from the locations of existing GSM-R BSs is provided by the results of preliminary radio planning for the Brno – Břeclav – Slovak border station – Kúty – Bratislava line, described in [25], Part C. On this section, with a total operational length of 133 km, the GSM-R system (in operation on the Czech side, and on the Slovak side only partially planned) comprises 23 base stations (unlike the source, the CD31601 Hrušky base station on Corridor 2 is also included in the coverage calculation) with an average cell ISD of 6.0 km. For coverage in the 1900 MHz band, preliminary planning indicates a further 21 gNBs, densifying the network to an average cell ISD of 3.2 km. The increase in the number of BS (gNB) for this band would therefore be 91 per cent. However, 8 of these sites are covered in the adjacent 1800 MHz band by MNO masts (see Section 2.3 for further details) and there is therefore an opportunity to utilise the MNO infrastructure for FRMCS through infrastructure sharing. The increase in the number of BS (gNB) sites to be constructed by IM would then be only 56 per cent. The deployment of FRMCS in the 1900 MHz band will therefore entail significant construction costs, even if passive infrastructure is shared between SŽ and MNO.

2.2.2 Interference with neighbouring bands

Despite the restrictions on transmission power in the band, there is mutual interference with the neighbouring allocated bands 1805–1880 MHz (downlink of band n8) and 1920–1980 MHz (uplink of band n1), which are used by MNO LTE systems with FDD and a 5 MHz channel width [4] [5].

- The main reason for the interference affecting operations in these bands is that even the basic (uncoordinated) transmitter mask for FRMCS base stations (gNB) assumes a higher level of receiver selectivity in the affected bands than is required by current Harmonised European Standards (see also [5]). It is anticipated that these higher selectivity requirements will, over time, be incorporated into the Harmonised European Standards; until then, mobile network operators in the 1920–1980 MHz band whose equipment does not meet this condition will only implement modifications to prevent potential interference following agreement with the IM, as Czech legislation does not permit the envisaged procedure solely on the basis of a request (notification) from the IM.
- Conversely, vehicle station receivers (generally MTs) of the FRMCS system must be sufficiently immune to transmitters of networks operating in the band up to 1880 MHz, and BS (gNB) receivers must be immune to the MT transmitters of these networks operating in the band above 1920 MHz.
- In the 1880–1920 MHz band, spectrum harmonisation is expected for the use of drones (UAS) by law enforcement agencies, with a possible impact in the form of changes to the requirements for FRMCS.
- Allocations for DECT operations (1880–1900 MHz) are also situated in close proximity to the n101 band. Systematic interference is not anticipated in this case due to the sporadic use of the DECT band and its dynamic channel selection (DCS) algorithm; measures will therefore only be necessary in exceptional cases, e.g. at control centres within the vicinity of a railway junction.

2.3 Possibilities for utilising MNO bands

‘Use of the MNO band’ for railway applications commonly refers to the use of MNO network resources for railway communications. These may serve various purposes:

- For use as a primary communication system **for critical services,** according to [5], the relevant part of the MNO network must meet the railway’s strict requirements regarding coverage, service availability, performance, border crossing/roaming conditions, and QoS support levels (including communication prioritisation and pre-emption), cyber security, maintenance and SLAs, as evidenced by certification [5], which MNO networks typically still do not meet.
- Essentially the same requirements apply when used as **a backup means** for critical communications, although the performance requirements may be lower. Border crossing/roaming requirements may be applied to entry/exit points for the IM network, operating in RMR bands.
- MNO networks that do not meet these requirements may only be used **for non-critical** (and currently also non-interoperable) **communications**. This approach already reflects the current use of public MNO networks utilising 4G LTE technology.

Responsibility and decision-making authority regarding the use of MNO bands for critical applications or even for FRMCS in general lies, in principle, with individual Member States within the EU, and the current V1 FRMCS standards (within the CCS TSI 2023) do not yet provide any support for this either. Rules for the licensing of reserved railway bands (RMR) have so far been established in EU countries; the current situation in the Czech Republic is described in the discussion of these bands in Chapters 2.1 and 2.2. The use of a specific band (not only MNO) for railway communications applications is further limited by

- **by the coverage of the railway network** with a signal of sufficient quality for the application in question,
- in the case of operation using proprietary technology, **by operating costs**; in the case of roaming or MOCN, by the agreed terms and usage **tariffs**;
- **interference** with networks in the RMR bands (both FRMCS and GSM-R), including networks beyond the boundaries of the railway’s own infrastructure, and unwanted interactions with antenna systems mounted on the roof of the rolling stock.

The coverage status of the main lines in the Czech Republic reflects the results of preliminary radio planning and its subsequent verification by measurement for the Brno – Břeclav – state border – Kúty – Bratislava line section, carried out as part of study [25], Part C. Coverage simulations were carried out as part of radio planning by one participating mobile network operator (MNO) for the 700 MHz (n28) and 2100 MHz (n1) bands, and verified by measurements for the 700 MHz (n28), 800 MHz (n20) and 1800 MHz (n3) bands. A total of 80 existing base stations in the vicinity of the route were included in the simulation. The measurement results for all operators are presented in the table as the percentage of measurement samples falling within the specified RSRP ranges:

Table 4 – Coverage ranges from the preliminary radio planning for MNO bands in the study [25]

RSRP range	-130 to -104 dBm	-104 to -90 dBm	more than -90 dBm
700 MHz band (n28)			
Czech side, 2 operators	21–94%	6–24%	0–54%
Slovak side, 1 operator	5%	31 per cent	64%
800 MHz band (n20)			
Czech side, 3 operators	0.2–0.4%	7–12%	88–93%
Slovak side, 2 operators	3–4%	28–30%	67–69%
1800 MHz band (n3)			
Czech side, 3 operators	27–31%	37–47%	26–32%
Slovak side, 2 operators	78–80%	9–22%	0.2–11%

The measurement results were in good agreement with the simulation results; poorer coverage was observed only on the Slovak side in the 1800 MHz band. Specifically, on the Czech side, the 700 MHz band is effectively covered by only one operator and the 1800 MHz band is covered weakly by all operators, whilst in Slovakia, the 1800 MHz band is not covered to a satisfactory standard by any operator. The planning identified a total of 4 sites to provide coverage in the 700 MHz band and a further 13 sites to provide coverage in the 2100 MHz band as well. Following coverage provision, the cells had a maximum ISD of 4.5 km (averaging just 2.3 km). 17 base stations (including one newly proposed for coverage) are located at the same or a nearby site as existing or planned base stations of the GSM-R or FRMCS systems, and thus offer potential for the sharing of passive infrastructure, particularly masts, between the FRMCS and MNO networks.

The most significant source of interference **affecting networks in the RMR bands** is that between an MNO-band transmitter (uplink) and an RMR-band receiver (downlink), which are installed and operating simultaneously on a vehicle in close proximity. In such a situation, the MNO-band transmitter must not block the RMR-band receiver or affect it through *spurious emissions* or *out-of-band emissions*. Table 5 summarises, for the individual MNO bands, the combinations requiring, according to
[30], as it is no longer possible to achieve the necessary suppression solely through the distance between the antennas in the confined space of the vehicle roof.

Table 5 – Overview of MNO bands relevant to railway applications

Interfering MNO band		Interfered-with RMR band	Minimum required attenuatio n	Use in the Czech Republic
Designation	Frequency range			
n28	703 MHz – 733 MHz / 758 MHz – 788 MHz	both	small (>20 dB)	LTE, 3 MNO allocations of 10 MHz each
n20	832 MHz – 862 MHz / 791 MHz – 821 MHz	both	small (>20 dB)	LTE, 3 MNO allocations of 10 MHz each
n8	880 MHz – 915 MHz / 925 MHz – 960 MHz	900 MHz	medium (>43 dB)	allocation in the Czech Republic for 2G only
n3	1710 MHz – 1785 MHz / 1805 MHz – 1880 MHz	1900 MHz	medium (>43 dB)	LTE, 3 MNO allocations 20–28 MHz
n1	1920 MHz – 1980 MHz / 2110 MHz – 2170 MHz	1900 MHz	high (>72 dB)	LTE, 3 MNO allocations of 20 MHz each
n7	2500 MHz – 2570 MHz / 2620 MHz – 2690 MHz	1900 MHz	medium (>43 dB)	LTE, 4 MNO allocations of 10–20 MHz
n78	3300 MHz – 3800 MHz (TDD)	1900 MHz	medium (>43 dB)	Allocation of part of band 3 to MNOs: 100–160 MHz

Interference is described in more detail for bands n1 and n3 in paragraph a and for band n8 in paragraph 2.1.2. MNO operations in bands n28 (700 MHz) and n20 (800 MHz) do not significantly affect operations in the RMR bands.

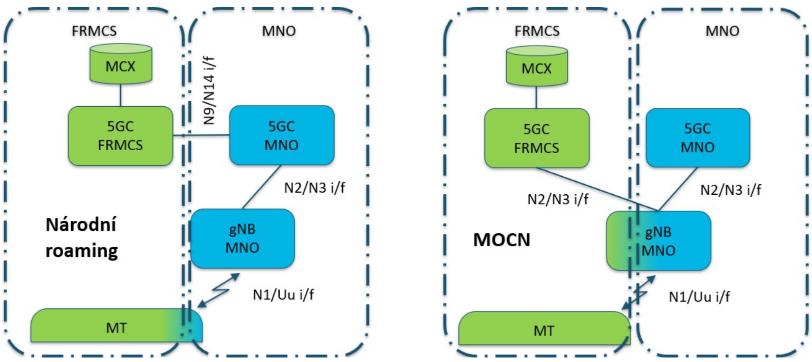
2.3.1 Network sharing schemes

The use of MNO access infrastructure (RAN) by IM operations is technically possible at two levels:

- **National roaming** is a scheme in which the IM operates part or all of the 5GC. Vehicles (field terminals) are equipped with an IM SIM and are registered as 'visiting' in the MNO's network. Traffic is routed via the MNO's core network to the IM's 5GC as if it were a foreign network. The disadvantage of this arrangement is the mediated connection between the 5G RAN and the IM's 5GC, which consequently does not have full control over the QoS provided to individual services. The domestic handover between MNO and IM networks (the IM's own RAN in RMR bands) is also complicated, involving, for example, IP re-routing of the MT and re-authentication.
- **MOCN** (Multiple Operator Core Networks), or **RAN sharing,** operates by connecting the 5GC IM via its own transmission system directly to the gNB of a cooperating operator. For communication, the gNB offers both the MNO's and the IM's PLMN IDs in parallel, along with a shared list of neighbouring cells; the ability to connect to them is determined by subscriber authorisations. IM terminals communicating within this architecture logically remain within the FRMCS domain, even though they are physically connected via the MNO's gNB.

The third and currently most widespread method is to use the MNO's network solely as a user – on SIM cards provided by the MNO, the IM or communications provider operates connections via access points (APs) to its private network, where the server resources implementing the service are located. Telemetry services based on IoT principles are typically operated in this way today, e.g. the collection of electricity meter data from vehicles or the remote monitoring and control of vehicle secondary systems (TCMS). Without additional QoS measures, the quality of service for these services does not exceed the standard commercial level and is insufficient for more demanding applications.

Figure 2 – 5G NR / RAN sharing options



RAN sharing based on MOCN principles can be regarded as a proven solution with specific benefits [22]:

- The architecture required to implement MOCN is defined by an open standard (specifically 3GPP TS 23.251). The principles of sharing are based on more than twenty years of practice by MNOs, which have been using it since the UMTS standard
- Sharing the 5G NR RAN between IMs and MNOs reduces the costs of the most extensive, and therefore most expensive, part of 5GS. The result is not only financial savings but, above all, the potential to accelerate the roll-out and deployment of the necessary services.
- An MNO RAN, which typically operates in higher bands than an RMR, can provide greater peak transmission capacity than the IM RAN itself. Although MNO networks are typically optimised for maximum downlink capacity, sharing can help improve network utilisation through IM traffic with precisely the opposite preferences
- Specific network-sharing modes can improve service availability, although the most commonly cited scenario involving the elimination of faults in the Core and gNB of a private network may not be based on correct assumptions.
- A direct connection between the Core and the RAN enables IM to directly manage end-to-end QoS, and communication is not dependent on the throughput and availability of the MNO's transmission systems and Core elements, which are dimensioned for standard commercial service levels. QoS control mechanisms may utilise only prioritisation via 5QI tags using the same procedures as in the RMR RAN, or utilise a portion of the capacity (RRB) allocated in the MNO's RAN via slicing.

Naturally, all aspects of sharing require an agreement on operational procedures between the MNO and the IM. This must regulate, at a minimum, the level of MNO network coverage suitable for railway applications and the availability/reliability of the infrastructure provided by the IM, which represents increased costs for the MNO. In terms of liability, in an MOCN, the MNO acts as a subcontractor to the IM, which is then solely responsible for the final form and quality of the service.

Networks for security and emergency services, established in this way in certain countries (FirstNet in the USA, Erilisverkot in Finland or the Radio Network of the Future in France), are usually cited as examples of successful MOCN deployments. However, a similar deployment for the railways must address the following differences:

- The operational needs of security and emergency services coincide with areas of higher population density, which are densely covered by MNO networks with sufficient capacity, so that traffic on the MNO RAN can achieve the required QoS. However, such coverage is not yet continuous in terms of supporting critical railway applications. Coverage of railway lines, particularly those with low traffic volumes, remains low and is currently of little interest to operators. On main lines, this is being addressed by development programmes such as the EU's '5G Strategic Deployment Agenda', which plans to cover up to 75,000 km of main lines, and it is there that sharing may have the expected effect. An example of such a situation, although currently planned to be used only for the sharing of passive infrastructure (structural components of gNB), is given in section 2.2.1.

- Critical communications for security and emergency services differ in detail and are often functionally simpler than those for railway applications. Whilst the first phases of 3GPP standardisation in Rel14 were already intended for the former use, not all railway requirements will be addressed even in the currently under development Rel19. These differences are, of course, addressed by the separate MCX Core IM, which is crucial for functionality; however, unlike solutions for security and emergency services, specific products for FRMCS are not yet available on the market.

The risks associated with the use of MOCN are primarily as follows:

- A mobile network operator (MNO) may fundamentally alter the technical operating conditions – the scope of system resources reserved during reconfigurations, upgrade to standard versions that do not meet railway requirements, or change the conditions under which various elements of the communication system were certified; alter coverage for operational or other reasons; or, in extreme cases,
- plan the decommissioning of jointly used technology and/or make its continued operation subject to unacceptable commercial terms,
- the cyber security of the operator's shared resources will not be at the level required for critical infrastructure. The expected consequence of an attack on the shared NG RAN would primarily be a denial of service (DoS) with a catastrophic impact on rail operations. Adequate cyber security is therefore a further parameter of the shared RAN, conditioning its use for MOCN.

2.4 Use of satellite communications

Satellite services for law enforcement and emergency services, as well as for civilian (commercial) use, providing online two-way communication, can be divided into:

- narrowband voice and data services,
- broadband internet access services, and
- satellite access integrated into 5G.

Other satellite services, such as positioning services and radio/television broadcasting, are one-way services and cannot therefore be considered as communications services for the purposes of the FMCS. This does not mean that they cannot be used in railway operations; specifically, according to the FRMCS SRS, GNSS is currently the main source of MT location information. An example of such a package of non-communication services is the EUSPA services, comprising positioning services (GNSS, specifically the Galileo system operated by EUSPA) and the EGNOS service (an augmentation system supplementing information from the basic Galileo or GPS services to improve positioning accuracy) and Copernicus (a satellite Earth observation service) [23]. However, these services are not the subject of this study.

2.4.1 Non-3GPP variants

Narrowband communication, originally intended for voice services for law enforcement and emergency services, emergency communications and the like, has over time expanded to include commercial applications in shipping and aviation, as well as professional use in remote areas. It is generally unsuitable for integration into FRMCS for several reasons:

- Specific services, such as various categories of voice calls or text messaging, utilise specific protocols that combine individual protocol layers, thereby rendering them incompatible with the FRMCS architecture, which strictly separates the transport, service and application layers. Specific protocols may not meet all the requirements placed on the FRMCS, such as support for QoS or service pre-emption, user and MT authorisation, transmission security (e.g. for ETCS), latency requirements, etc. Such services can only exist outside the FRMCS, connected via appropriate gateways.
- Narrowband transparent packet data transmission is not suitable as a transport layer beneath the FRMCS/MCX service layer, as its transmission capacity is insufficient even for overhead data flows such as IMS/MCX signalling (control plane) or encryption redundancy.
- A series of projects assessing the suitability of satellite systems for railway applications has so far demonstrated insufficient service availability on moving vehicles, caused by shadowing from terrain features and built-up areas, even for very narrow-band systems such as GNSS.

Broadband satellite access is commonly offered as B2C internet access with speeds of up to 150 Mb/s, subject to the usual restrictions associated with this type of service – fixed-term contracts and Fair Usage Policies (FUPs) once the data limit is reached (in the order of tens of GB per month) [13]. The services offered by individual providers vary in terms of speed, latency, stability and, of course, tariff conditions. There are relatively few providers – (for North America) Starink (LEO), Viasat and Hughesnet (GEO). The use of this type of satellite communication within the FRMCS is hindered by

- the absolutely minimal, and for MCX/FRMCS insufficient, service management capabilities (session management, QoS support, security).
- the use of fixed-directional parabolic antennas measuring up to 0.75 m [31], which cannot be installed on a railway vehicle. The transmission is most likely not equipped to handle rapid signal drop-outs or Doppler effects caused by the movement of the moving target (MT) and shadowing by terrain features and built-up areas, as is the case with narrowband receivers.

2.4.2 Satellite communications within 5G

Satellite communications within the 3GPP framework have been under development since the Rel14 studies and the first Rel15 standards, primarily as an alternative to terrestrial RAN (4G LTE and 5G NR) for areas not covered or where terrestrial coverage is uneconomical (e.g. sparsely populated areas) and as links offering greater resilience than terrestrial infrastructure, including for critical communications [12]. In the form in which it has been progressively standardised since Rel17 [14], it meets the IMT-2020 mobile communication requirements as defined by ITU-R. The deployment of satellite access for critical (MCX) services is being prepared for the forthcoming Rel19. The benefits of satellite communications are expected primarily for critical services and industrial applications requiring continuous coverage. Within the framework of the UIC FRMCS FRS and SRS standards, it can therefore be regarded as one of the 3GPP access options and should thus be utilised as an integral part of 5GS, in practical implementation on a vehicle as an FRMCS GW satellite radio module with direct communication to a satellite transponder.

Other use cases, such as a satellite backhaul for terrestrial gNBs, satellite access for IoT, relaying of satellite traffic between MTs, content broadcast/multicast services, support for non-continuous satellite coverage, edge computing on the satellite, and traffic routing between MTs directly to the satellite gNB (which cannot be used by the higher-level IMS/MCX service layer) (all Rel18) are not relevant for use within the FRMCS. Similarly, given the mandatory inclusion of GNSS positioning in FRMCS, there is no need for mechanisms enabling the connection of MTs without GNSS support, as planned from Rel19 onwards.

3GPP standardisation work relates more generally to 'non-terrestrial' networks (Non-terrestrial Networks, **NTN**) are networks with communication resources located on satellites in various types of orbit (altitude and shape), but also on unmanned aerial vehicles heavier or lighter than air (**HAPS**) operating at altitudes of 8–50 km. Within the FRMCS, in the FR1 frequency band (0.4–7.1 GHz), low Earth orbit (**LEO**) satellites (or very low Earth orbit (VLEO) satellites) 500–2,000 km due to their low latency, and geostationary systems (**GEO**) with an orbit at an altitude of 35,768 km due to their stationary position above the service area.

In the 3GPP studies [12] and subsequently in the SATis5 project [14], architectures were developed featuring a link between the mobile terminal (MT), the satellite (or HAPS transponder) and the ground base station (gateway) in two variants

- without signal regeneration (**transparent link**, bent-pipe), in which the signal is processed on the satellite solely in analogue form (filtering, frequency shifting, amplification), and which, within the 5G NR architecture, operates as a DU or RRH. This type of link is used primarily with GEO satellites and, up to Rel17, was the only one to have been developed into specific standards.
- An alternative is **the regenerative link** (non-transparent), where, in addition to the aforementioned analogue operations, the satellite performs signal demodulation and decoding, switching or routing, and re-encoding and modulation, with the satellite acting as a fully-fledged gNB (both DU and CU). This type is used primarily for LEO links in the S-band (1–6 GHz), where it enables the necessary retransmission of links (Inter-Satellite Links, ISL) between satellites grouped in large constellations, only some of which are directly visible from the ground station (GS), forming a gateway to terrestrial networks. It will be fully incorporated into the 3GPP standards from Release 19 onwards.

The bands up to 7.1 GHz (within the FR1 range), intended for use in the 3GPP standard and applicable to railway communications, are summarised in Table 6. All these bands are dual-mode with FDD operation:

Table 6 – Bands designated for railway satellite communications

Designation	UL / DL frequency range	3GPP support	Current allocation in the Czech Republic	Note
n256	1980 – 2010 MHz / 2170 – 2200 MHz	Rel17	IMT mobile satellite service, 2 × 15 MHz, secondary use by radar systems	in close proximity to the terrestrial band n1 (2100 MHz), primarily for HAPS (low elevation)
n255	1626.5 – 1660 MHz / 1525 – 1559 MHz	Rel17	Mobile satellite service; secondary use of the 1–20 MHz bands by various services, including non-civil services; priority use of the downlink for maritime distress communications (GDMSS)	30 MHz extended channel from Rel18
n254	1610 – 1626 MHz / 2483.5 – 2500 MHz	Rel18	Band primarily used for aeronautical navigation, shared with other services; downlink primarily for industrial, scientific and medical applications	downlink in close proximity to the terrestrial band n7 (2600 MHz)

The 3GPP study [12] and subsequent in-depth testing in the SATis5 project [14] also revealed the main technical challenges associated with integrating satellite links into 5G:

- The radio signal for all satellite links is more susceptible to the effects of atmospheric phenomena as it passes through the troposphere (for frequencies above 6 GHz and low elevations) or the ionosphere (up to 6 GHz).
- Satellite signal coverage cells are many times larger than terrestrial ones, and coverage is therefore far more uneven than with terrestrial 5G NR. Cells may extend beyond national borders or the boundaries of a specific network, meaning that a single cell may belong to several 5GCs with different commercial or even legislative conditions of use. Due to these limitations, large areas must typically be divided into smaller ones. At the physical layer, this division is represented by radiation beams; in the logical configuration, it is mapped by virtual cells with dimensions similar to those of terrestrial systems, which facilitates the integration of the satellite RAN into a 5GC, as well as meeting the standard's requirement for a fixed tracking area.
- The use of GEO satellites poses particular challenges, primarily in terms of the physical layer of the link. Due to the great distance of the link, they operate with a minimal signal-to-noise ratio (SNR) and, as with non-3GPP links, the satellite transceiver requires a fixed-directional parabolic antenna, which cannot be installed on a railway vehicle. The transmission is unable to compensate for rapid signal drifts caused by the movement of the MT. Connections to GEO satellites are therefore not used for direct links to the MT, but for backhaul to secondary terrestrial gNBs.
- The high latency of these links (several tenths of a second for GEO links) is not only unsuitable for certain types of services, but also requires the adaptation of certain internal network control mechanisms, as described below.
- For other types of satellites, their position relative to the Earth's surface changes over time, and this (predictable) movement must be compensated for by various means in order to minimise the handovers it forces. Coverage provided by a satellite transmitter is either mobile (moving with the satellite) or the covered area is stabilised by beamforming whilst the satellite moves above the horizon. Controlling the transmission in relation to the satellite's movement, and ensuring that the MT is covered by a specific transmission lobe into which the coverage area is divided, requires **knowledge of the MT's position**, which must be determined by means outside the satellite system itself. According to current standards, the primary source of position is the GNSS service, with a required accuracy of approximately 2 km; from Rel18 onwards, this is verified by the 5G system itself with an accuracy of 5–10 km using delay measurements. The satellite terminal thus determines not only its own position but also other parameters of the access satellite (satellite orbit and time advance), which are necessary for establishing a connection with random access to the medium (MAC), routing traffic to the 5GC (PLMN selection) and its billing, supporting emergency services – typically location-dependent – compliance with local legislation, etc.
- Furthermore, LEO satellites move at high speeds relative to the Earth's surface, which introduces additional effects – Doppler frequency shift and rapid changes in delay.
- All the consequences described, arising from greater distances and satellite movement, require **protocol extensions to** the main radio interface protocols – the Medium Access Control (MAC) layer, the Radio Link Control (RLC) layer at the physical layer, and the Packet Data Convergence Protocol (PDCP) – to include supplementary information on the MT's position and the satellite's orbit, extended cell identification, more comprehensive handover management, modified HARQ timing or transmit power control, addressing the consequences of distance and satellite movement such as high latency or Doppler frequency shift. For connections terminated at the MT, all these extensions must be supported directly by the MT.
- The requirement for mobility between satellite and other types of 5G access also necessitates the incorporation of some of the aforementioned elements (e.g. extended localisation of satellite cells in the neighbouring cell list) into terrestrial 5G NR protocols. When using satellite communications within the FRMCS, these additions will need to be incorporated into its technical standards and supported by MT on vehicles and, where applicable, by other users.

Unlike RMR communications, satellite access will not be a system owned or operated by the IM, but will be purchased as a service from **commercial or public-sector entities**; an extreme variant is the use of satellite links linked to **cloud** services, an example of which is Amazon's AWS-GSN ground stations in the USA, involved in the SATis5 project [14].

However, satellite services integrated into 5GS are not currently available on the market. The technology is still in the piloting and testing phase as part of various programmes centred around the SATis5 demonstration programme, which forms part of the ESA ARTES project [32], where railway applications fall under the use case of satellite connectivity for moving MTs (such as trains and, in particular, high-speed rail) [11], addressed in 3GPP from Release 16 onwards, namely advanced mobile broadband (Enhanced Mobile Broadband, eMBB – Communications on-the-Move, COTM) or use case 1: High Reliability Communications (HRC, demonstrated using the commercial GEO satellite ASTRA 2F operated by SES) [14]. The final use case relates to multi-network connectivity via both terrestrial and satellite networks, which can also be utilised to increase capacity or for load balancing between networks. Planned communications between infrastructure elements (URS applications 6.10 and 6.12, see Chapter 1.1) represent the use case of massive machine-type communications (Massive Machine Type Communications, mMTC) – local Internet of Things (IoT) services.

An example of a satellite system operated in part by a public-law body – specifically the EU – is **IRIS^2**(Infrastructure for Resilience, Interconnectivity and Security by Satellite), which is being developed with the participation of the ESA, EUSPA and the private sector, represented by a consortium of operators comprising SES and Eutelsat [17]. It is a hybrid system utilising LEO, MEO and GEO satellites, intended **primarily for use by government institutions** and security forces within the framework of EUSPA's GOVSATCOM [15]. This purpose is also reflected in its technical characteristics – the provision primarily of narrowband services, strongly secured by EuroQCI quantum cryptography. However, the system is to **apply the principles of 5G NTN** to the greatest possible extent, and its subsequent commercial phase envisages both fixed and mobile broadband access services, including services for the transport sector (as yet unspecified), B2B communication links and connectivity to cloud services [16] Services for government institutions (Hardgov) are expected to achieve full operation and global coverage in 2027.

The integration of satellite access in all the variants mentioned with the 5GC typically owned by IM will follow the scheme set out in section 2.3.1. As with MNO terrestrial networks (section 2.3), the sharing of satellite RAN resources should primarily be addressed via a slice designated for railway use or, at the very least, via roaming. The risks associated with the use of satellite links for IM, for the various types of interconnection with MNOs as set out in Chapter 2.3.1, are as follows:

- A satellite network operator providing only the service (own SIM) or roaming may fundamentally alter the commercial terms of operation, in particular the price of the service, which is or will be several times higher than the price of analogous terrestrial network services
- A foreign satellite network operator may not offer sharing or roaming on acceptable commercial terms, or may not offer it at all
- A satellite network operator providing roaming or cooperating on the MOCN may alter the technical conditions – the scope of reserved system resources during reconfigurations, upgrades to standard versions that do not meet railway requirements, or changes to the conditions under which various elements of the communication system were certified.
- The parameters of available commercial satellite RANs may not meet the requirements of railway standards, particularly regarding coverage continuity (especially for LEO networks, where only a fraction of the target number of satellites has been activated so far), QoS management (including pre-emption) and security.
- The latency achieved for each service will need to be assessed on a case-by-case basis. For access via GEO satellites, tests at the SATis5 test site showed values in excess of 200 ms, which do not meet the limits for voice services and communication control (signalling) as specified by the FRMCS SRS. Compliant values can only be expected for services based on LEO satellites. Conversely, with a channel bandwidth of 15–30 MHz and the spectral densities achieved, as per [32], link throughput can be expected to exceed 10 Mb/s, which is comparable to the throughput of the RMR band in terrestrial systems.
- As with narrowband systems and GNSS, a significant impact from shadowing caused by terrain features and built-up areas can be expected, which may render satellite links unusable in urban environments and within station premises.
- Specifically in the Czech Republic, only the n256 band, immediately adjacent to the terrestrial mobile band n1, has been allocated for this type of satellite communication. The use of both bands on a vehicle will not be possible due to insufficient separation. It will be necessary to assess the situation in neighbouring countries and networks to determine whether this band is also used there and is therefore interoperable.

2.5 Non-3GPP technologies

Other radio communication standards, which are potentially usable or have historically been used to support railway operations, include narrowband terrestrial radio transmissions (both analogue and digital), transmission technologies covered by the collective term 'Wi-Fi', and satellite links (of the non-3GPP type), which have already been discussed separately in section 2.4.1.

The prospects for integrating narrowband systems into the 5G / FRMCS environment are very low:

- Without further fundamental measures (specific gateways), analogue systems are incompatible with a digital/packet-based environment. The benefits of such a complex integration are minimal, as analogue systems essentially provide only voice services, or data transmission at speeds of up to 5 kb/s, which has no use in the FRMCS environment.
- **Digital narrowband standards** such as DMR, P25 or TETRA provide specific services, such as various categories of voice calls or text messaging, for which they utilise specific protocols that combine individual protocol layers and are therefore not directly compatible with the FRMCS architecture. At the service layer (MCX), they can be integrated via gateways standardised within the 3GPP MCX architecture (3GPP TS23.283 and related standards), which also ensure the minimum necessary integration into mechanisms for service pre-emption, user and MT authorisation, transmission security, etc. However, both voice and data services have significantly lower functionality than that of native FRMCS mobile terminals and **will never be fully interoperable**.
- The narrowband transparent packet data transmission provided by these systems cannot be used as a transport layer beneath the FRMCS/MCX service layer, as its **transmission capacity is insufficient** even for overhead data flows such as IMS/MCX signalling (control plane) or encryption redundancy.

Wireless **data access** systems (WLAN), collectively referred to as **Wi-Fi**, are systems standardised by the IEEE 802.11 series of standards. They are primarily intended for terrestrial, stationary access to packet-switched services at the link level (LAN), optimised for connection to an underlying fixed network based on Ethernet standards (IEEE 802.1). Several generations of these standards are characterised by theoretical data rates of tens to hundreds of Mb/s, achieved using OFDM or similar modulation techniques on channels 20–40 MHz wide [18]. Due to this bandwidth, they are, with a few exceptions, standardised for the 2–6 GHz band (FR2); specifically, for FRMCS [SRS1.2.0] communications, the use of the 2.4 GHz Wi-Fi bands

- 2.4 GHz (2.400 GHz to 2.4835 GHz),
- 5 GHz (5.150 GHz to 5.350 GHz, 5.470 GHz to 5.725 GHz and 5.735 GHz to 5.875 GHz) and
- 6 GHz (5.945 GHz to 6.425 GHz).

Due to these high operating frequencies, the high modulation density used and the resulting high signal-to-noise ratio (SNR) requirements, as well as the low transmission power compared to mobile networks, Wi-Fi operates in both indoor and outdoor environments with a relatively short range of just a few hundred metres. The relatively high data rates of Wi-Fi, compared with NR communications in the RMR bands (Chapter 2.6), may be beneficial for railway operations; however, its use is limited to specific conditions:

- Given the aforementioned short range of Wi-Fi, providing continuous coverage along a railway line is highly problematic, even though, for example, communication scenarios for high-speed rail (HSR) with such set-ups (though typically implemented using 5G NR in the 3.5 GHz band) do take this into account. On conventional lines, however, the capital-intensive construction work will not be economically justifiable, and Wi-Fi access points (APs) will only be installed at gNB locations in the RMR bands. **Coverage** will therefore, in principle**,** be **point-to-point, not exceeding 20 per cent of the line's length**, with regular connection outages lasting tens of seconds. Such a communication environment **is unsuitable for critical applications,** and even non-critical applications must be prepared for this mode of operation (through data buffering for transmission, rapid authentication and authorisation mechanisms, etc.). Some of these tasks can be handled by WLAN management mechanisms [21], based on both proprietary and open standards, but the batch nature of communication in such a configuration will remain.
- Wi-Fi communication is intended for stationary or nomadic use. The stated range for outdoor environments typically applies to line-of-sight (LOS) links. The link will therefore be **affected by the movement** of the **train** and the associated Doppler shifts in the signal and rapid signal fading. The Wi-Fi transmission mechanism is not designed to cope with the second of these effects in particular, and link performance will be severely degraded. It may therefore be the case that Wi-Fi access points (APs) will only be usable in areas where train speeds are low, such as **large railway stations, marshalling yards and depots**. In such cases, the linear coverage of the line will be only fractions of a per cent, although the temporal coverage will be more favourable – in the order of a few per cent. The specific communication requirements of the applications mentioned above will be even more demanding in such circumstances.

It follows from the above that communication using Wi-Fi standards on rolling stock may be **of** only **marginal significance** in the railway environment **for selected non-critical applications**; examples from the applications classified according to the FRMCS URS (Chapter 1.1) include: Communication at stations and service facilities (6.8), Train telemetry communication (6.9), data communication for train departures (6.18) or the transmission of CCTV archives (6.22).

2.6 Meeting communication requirements

The communication requirements for the sets of applications envisaged for migration and for the target scope of critical communication under FRMCS are quantified, for example, in [5] based on the 2018 UIC model. Similar data on a more limited scale – for basic applications migrated from GSM-R: voice services, ATP/ETCS and ATO (up to GoA2) – are also provided by [8]. The requirements were quantified in four variants, of which only some have been selected for the purposes of this study:

- **Pkg #2** – the full target set of applications according to [5], including critical video, which, whilst still not complete in comparison with the full USR requirements (see Section 1.1), adequately covers that part of the requirements which is sufficiently defined by the associated UIC standards and is therefore of genuine interest to operators and infrastructure managers. The full set considered theoretically in [5] without the critical video is, however, unusual in that it is the only one to exhibit high asymmetry in favour of the UL, and the optimal approach for it would be to use TDD transmission with the option of a UL/DL ratio of 90:10, i.e. in the 1900 MHz band; however, it is not part of the most likely scenario: Pkg #1R > addition of critical video > expansion to Pkg #2. For this scenario, the asymmetry provided by the 1900 MHz TDD band is not particularly significant; however, it can (with a different ratio setting, e.g. 70:30) be utilised, for example, to support the target set Pkg #2.

- **Pkg #1** – the set of applications required under [5] already during the migration from GSM-R,
- **Pkg #1R** – the same set, but reduced by the transmission capacity required for the most demanding critical video application (URS Chapter 5.27). Compared with the estimated requirements of the existing suite operated on GSM-R (voice services, ATP/ETCS and ATO up to GoA2) according to Annex [28], this is approximately double, as even without video it includes applications currently operated outside GSM-R (emergency calls to the public network, remote control of traction units, basic vehicle telematics).

Table 7 compares these requirements with the available transmission capacities of 5G transport, quantified by simulations in [3]:

- **Transmission capacity requirements** are quantified for an individual train and for a RAN cell. The operational parameters (for the various segments considered: an average RAN cell radius of 8 km and a density of 0.33 to 0.67 trains per km, i.e. 2.6 to 5.4 trains registered to a single cell) roughly correspond to some simulation variants, but are used solely to calculate the total required cell capacity and do not affect the requirements of a single train.
- By contrast, **the simulated transmission capacities** depend heavily on the cell diameter and the number of trains registered within it; the average number of trains per cell in the simulation is therefore shown in the table. However, the values selected for the simulation correspond well to the reality on the SŽ network, as quantified in more detail, for example, for the purposes of study [25]. There, traffic densities reach values close to 0.4 trains per km, and the average ISD cell sizes are also in good agreement – 4–9 km for GSM-R (900 MHz band), whilst the proposed values for the 1900 MHz band are 1.8–4.9 km.

The following also applies to the available transmission capacity values used in the comparison:

- From the simulation results, the 50th percentile values of the transmission rate distribution – determined for a large set of trains moving through the simulated cells – have been selected for comparison. It can be expected that a (moving) train will have at least this transmission rate available for half of its journey time. For the sake of completeness, values at the extremes of each cell type, represented in the simulations by the 5th percentile, are also given. The published simulation results do not include average data transfer rates, which would be more relevant for calculating the volume of data transferred.
- The achievable speeds are taken everywhere for settings with the maximum permitted transmission power (uplink up to 31 dBm, 1900 MHz downlink 63 dBm, 900 MHz downlink 46 dBm). In areas where coverage conditions are more favourable, the downlink transmission power may be reduced; the uplink power will be reduced automatically by mandatory control.
- From the simulated MIMO variants, those which, according to [8], are most likely to be implementable on vehicles operating in conjunction with GSM-R were selected for comparison. The main limitation here lies on the vehicle side, where, for space reasons, no more than two antennas can be expected; of these, only one transmit antenna is permitted under the Rel18 standards. The MIMO configurations are therefore limited to 1xN for the uplink and Nx2 for the downlink. As simulations in [3] showed minimal benefits from Nx8 configurations, the number of antennas on the gNB is also limited to 4. Consequently, the MIMO configurations selected for estimating achievable throughputs are 1x4 for the uplink and 4x2 (or 2x2, where this yields better results) for the downlink.

Table 7 – Comparison of required and available transmission capacities in the RMR bands

Capacity required per train	Trains per cell	Uplink [Mb/s]	Downlink [Mb/s]
Required capacity for Pkg #1R per train	up to 6	0.19	0.2
Required capacity of Pkg #1 for a single train	up to 6	3.49	3.5
Required capacity of Pkg #2 for a single train	up to 6	7.42	4.38
Achievable capacities in the 1900 MHz band			
in open countryside, ISD 8 km	4	1.3 – 2.2/2.3*	0.2*/1.2 – 3.3
at the edge of such a cell	4	0.4 – 0.8/1.4*	0.2*/0.8 – 1.2
in open countryside, ISD 4 km	2	4.3 – 5.4/10.0*	1.2* – 6.0
at the edge of such a cell	2	2.9 – 3.3/6.2*	0.4* – 1.8
in an urban environment (built-up area), ISD 2 km	2	1.4 – 4.6/8.6*	0.4*/2.2 – 8.7
at the edge of such a cell	2	0.5 – 1.6/2.9*	0.3*/1.3 – 3.5
Achievable capacities in the 900 MHz band			
in open countryside, ISD 8 km	4	2.1 – 2.5	2.2 – 3.0
at the edge of such a cell	4	1.0 – 1.6	1.1 – 1.4
in an urban environment (built-up area), ISD 4 km	4	0.7 – 1.7	1.0 – 2.7

at the edge of such a cell	4	0.2 – 0.4	0.4 – 1.1
in an urban environment (built-up area), ISD 2 km	2	2.5 – 4.6	2.6–6.1
at the edge of such a cell	2	1.6 – 3.3	0.8 – 2.1

Although the values for achievable transmission rates show considerable variation across different simulation methods, the following conclusions can be drawn from the table:

- **In the initial phase** of migration, FRMCS will, with a high degree of probability, be able to provide **the necessary capacity under all operating conditions** for applications within the range currently supported by GSM-R (i.e. with requirements below the Pkg #1R level), within which IM, including the Czech operator, plans to carry out the migration. Contrary to general expectations, this also applies to 1900 MHz cells with an ISD of 8 km, i.e. 1900 MHz operation on a non-densified gNB network.
- However, with **the deployment of the first critical video applications** (Pkg #1), **limitations can be expected** at the cell edges, manifesting as congestion and connection instability on a moving train; at best, this will result in fluctuations in transmission latency at intervals that will be unacceptable for the application in question. The situation will be worse in the 900 MHz band, where even a gNB network with an ISD of 4 km – i.e. denser than GSM-R – may not meet these requirements, particularly in the uplink. In the 1900 MHz band, capacity can be optimised by appropriately setting the DL/UL multiplex ratio; however, the extreme simulated ratio of 90:10 (values marked with * in the table) disproportionately reduces the guaranteed downlink capacity and is therefore not a universal solution. With the arrival of further applications, represented by Pkg #2, the situation will deteriorate further, and it will only be possible to meet the requirements in special cases (shaded cells in the table). The only solution will then be to split the communication across multiple bands using Multipath / Application-specific path selection as per [30], i.e. the existence of an overlapping network in both RMR bands or the transfer of part of the traffic to MNO networks, including critical traffic, as Pkg #2 comprises only telemetry and remote control of on-board technologies (URS Chapters 6.9 / 6-11) amongst non-critical applications. The inclusion of selected MNO bands in the FRMCS specifications (primarily TOBA) must take place within the scope of FRMCS V3, as their use must be interoperable to support critical applications.

3 Possible migration scenarios

The necessity and timeframe for the migration of existing mobile railway communications are determined by the end of GSM-R support after 2035, when, according to [1], the greatest challenges will be maintaining staff qualifications and procuring/maintaining replacement hardware to ensure its operation. At the same time, the cornerstones for the successor FRMCS technology – the allocation of reserved frequency bands (RMR) as recommended by ECC 20/02 and the update to the CCS TSI, incorporating the FRMCS V1 standards in 2023 – are considered to be in place.

According to [7], the migration procedures, in line with the outcomes of discussions with representatives of the railway sector, are subject to the following conditions:

- The GSM-R service must remain available throughout the planned transition period to the extent specified (the infrastructure manager must notify the operators concerned of the termination and/or significant restrictions on operations a relatively long time in advance, as stipulated by the CCS TSI) whilst maintaining both quality and the original coverage.
- The proportion of rolling stock communicating using a specific standard is always higher than the proportion of that standard in the infrastructure. This applies both to the FRMCS system being deployed and to the GSM-R system being replaced. Consequently, during the period when the migration of rolling stock and the migration of infrastructure overlap, a certain proportion of rolling stock will need to be capable of communicating using both standards.
- Communication using the FRMCS standard may share the 900 MHz band with GSM-R operations (details are discussed in Chapter 2.1); it may be deployed in the 1900 MHz band whilst allowing GSM-R operations to continue in the 900 MHz band in full until their cessation (an option discussed in detail in Chapter 2.2); various combinations of both approaches may be deployed, utilising MNO bands either temporarily or permanently, including for critical applications.
- The duration of the migration period is influenced, both on the infrastructure manager's side (construction of the ground-based part of the system) and on the operators' side (installation of new on-board parts of the system), by the commercial availability of the necessary components, installation, construction and workshop capacities, the potential volume and available sources of funding, and the operationally acceptable extent of service interruptions or vehicle out-of-service periods required for the necessary modifications. In the first case, a key factor is the extent to which existing passive infrastructure (the civil engineering part of the system) can be utilised; in the second, a significant factor is the financial and time costs associated with approving the type changes required by the installation, which are likely to increase further with the transfer of approval processes to the ERA. Some of the factors mentioned are interdependent; for example, purchase prices typically rise as required deadlines are shortened below a certain threshold, provided such deadlines are at all practically achievable.
- The pace of introduction (or increase in demand) for new applications which, for various reasons, can no longer be supported by the GSM-R system or other existing means of communication. Whilst this applies to high-performance or non-interoperable applications (Chapter 1.1), these will not be subject to migration between GSM-R and FRMCS and will only be integrated into the FRMCS system in subsequent phases,
- A legislative requirement is compliance with the provisions of TSI CCS Annex I §7.3.1.2, according to which the cessation of operations on individual sections must be notified by the IM **via an entry in the RINF five years in advance**.

The preferred duration of the migration period for each entity depends on the preferred or feasible cost structure:

- From **an investment** perspective, **a longer period** is generally more advantageous. The volume of investment in individual years may be constrained by various factors, and the acquisition costs for technology, its installation and commissioning, and any civil engineering works increase as construction deadlines are brought forward, due to manufacturers' and suppliers' responses to excess demand, greater utilisation of limited installation capacities, and so on. In the case of HV equipment, this is compounded by a higher proportion of the existing fleet being replaced during a longer migration period, where, in accordance with standard practice, the cost of communication equipment for new HVs is not included in the costs of technology replacement.
- From the perspective of **operating costs**, **a shorter timeframe** is more advantageous. This is particularly evident for those entities which, in individual scenarios, build and gradually commission their section ahead of schedule and, for the remainder of the migration period, bear the dual operating costs of both the old and new technologies.
- **An earlier start and end to the migration period are advantageous for both parties**. On the one hand, during the phase-out of GSM-R technology on the suppliers' side after 2030, a significant increase in GSM-R operating costs is expected (primarily the purchase/pre-stocking and storage of spare parts, and support services from manufacturers); furthermore, for networks where the planned GSM-R coverage will not be completed by the start of the migration, there is the added saving of avoiding sunk costs in components of the GSM-R system operated on a short-term basis, the majority of which are not expected to be used within the FRMCS.

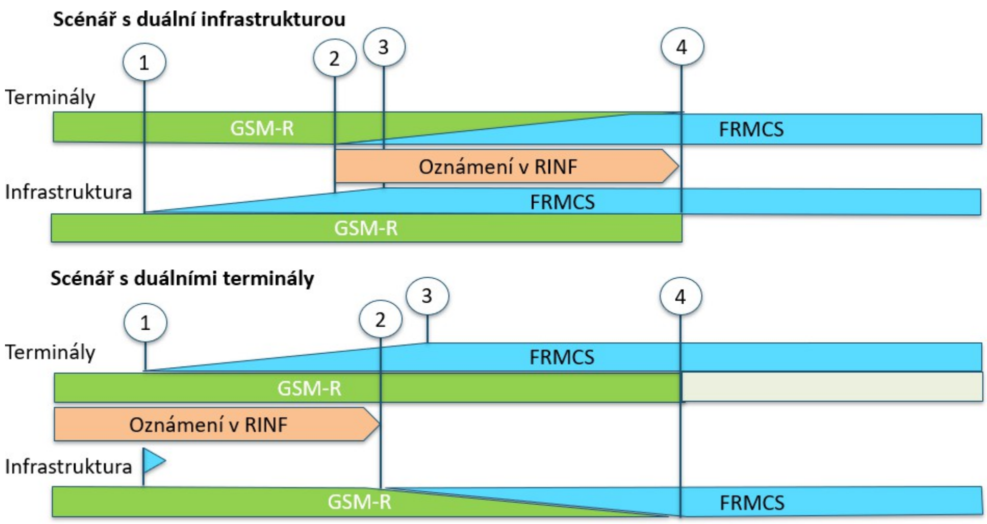
3.1 Theoretical scenarios

Theoretically, possible scenarios were studied at the instigation of the ERA as early as 2015 [2], at a stage when neither the basic technical characteristics of the successor FRMCS system – the frequency bands to be used – nor its more detailed architecture were yet known. An economic model was used to evaluate various options for two basic migration approaches against a 'baseline scenario':

- an approach involving a relatively long (with several variants) **period of overlap between the two systems on the infrastructure**, during which operators gradually implement the new technology on vehicles, or on other terminals linked to staff (mobile handheld) or infrastructure (stationary);
- an approach **utilising dual terminals**, in which the infrastructure technology is upgraded (on a local or network-wide scale, depending on the specific variant) within a short timeframe (essentially by switching from one standard to the other). Under this approach, transport operators equip their vehicles in advance with terminals capable of communicating in both standards and are therefore able to use them on both modernised and non-modernised sections of the network. This basic variant also includes a variant involving the replacement of terminal technology in parallel with the infrastructure (within a short timeframe and in very close coordination with the IM), which subsequent developments have shown to be unrealistic.

Both scenarios are being studied as blanket approaches – they are applied uniformly across all line sections in accordance with the relevant timetable. In addition to these blanket approaches to migration, there are also procedures utilising different methods specific to each location. These include, for example, extending the 900 MHz network coverage with 1900 MHz gNB 'islands' or 1900 MHz transition sections at domain boundaries, examples of which are given in section 2.2 and [7]. The scenarios for this purpose did not include preparatory steps such as tests on test tracks, pilot runs or the replacement of Class B communication systems, which are typically part of specific scenarios for railway operators (see Chapter 0).

Figure 3 – Basic theoretical migration scenarios



The theoretical **migration** process **with dual infrastructure** comprises the following steps:

1: Initial phase
Both the infrastructure manager and operators are using GSM-R in operation. The infrastructure manager builds the FRMCS system in advance (across the entire network or part of it), but may only put it into operation to the limited extent necessary for its own testing and preparation for the migration of rolling stock – pilot schemes, testing and type approval. Operators can use this time for commercial and technical preparation for the subsequent retrofitting of rolling stock (selection of suppliers, prototype installations and testing).

2: The IM puts the FRMCS into operation across the entire network or a significant part of it; however, the GSM-R infrastructure remains in operation. No later than at this stage, the IM must announce the first dates for the cessation of GSM-R operations in accordance with TSI CCS Annex I §7.3.1.2. Operators commence the serial retrofitting of their rolling stock (and other communication terminals) to the FRMCS system. The costs of maintaining GSM-R in operation during this phase are expected to rise gradually, with the rate of increase accelerating as the announced end of support in 2035 approaches.

3: The IM is completing the roll-out of the FRMCS infrastructure, which modernised rolling stock and terminals can use without restriction; support for GSM-R is no longer required on these systems. The costs to the IM of maintaining the phased-out GSM-R system continue to rise during this phase.

4: The fleet renewal of the relevant operators is complete; all vehicles (other users) utilise the FRMCS infrastructure. The IM ceases GSM-R operations as it is no longer in use. FRMCS CAPEX in this phase remains at a certain level due to the construction/equipping of further lines and the fitting out of new vehicles.

Migration **using dual terminals** consists of the following basic steps:

1: Preparatory phase
Both the infrastructure and transport operators are using GSM-R in operation, but the IM is halting its development. The IM was required to announce the initial dates for the cessation of GSM-R operations well in advance, in accordance with TSI CCS Annex I §7.3.1.2. During this stage, operators retrofit their rolling stock with FRMCS-compatible terminals in advance, or upgrade to terminals supporting both technologies. During this phase, all preparatory stages for this retrofitting must take place, such as the selection of suppliers, prototype installations and their type approval. To this end, the IM must ensure the minimum conditions are met by establishing a sufficient pilot section of the FRMCS for testing.

2: Commencement of deployment A significant proportion of rolling stock has been retrofitted with the new FRMCS. The IM generally begins to commission the FRMCS in sections of the network and ceases GSM-R operations. The scope for using non-retrofitted rolling stock declines sharply (the proportion of rolling stock equipped with FRMCS must generally be higher than the proportion of FRMCS on the IM's network).

3: Operators complete the retrofitting of their rolling stock to support FRMCS, whilst the IM continues to upgrade the infrastructure to FRMCS. In the modernised part of the network, operators utilise the FRMCS infrastructure, for which their rolling stock is already equipped. The costs of maintaining the GSM-R legacy system are expected to rise gradually during this phase, with the rate of increase accelerating following the announced end of support in 2035.

4: IM has completed the construction and commissioning of FRMCS across the entire network and is phasing out GSM-R operations. FRMCS CAPEX in this phase remains at a certain level due to the construction and equipping of further lines.

The implementation conditions and outcomes differ in many respects between the two scenarios:

- The different phases and conditions under which **the IM announces the dates for the phasing out of GSM-R**, as required by the CCS TSI in Annex I, Section 7.3.1.2. In each migration process, time buffers must be allowed to meet the required five-year advance notice period; these **time buffers are greater in the dual-infrastructure scenario**, in which the retrofitting of rolling stock takes place only in subsequent stages. It is practically impossible to expect rolling stock retrofitting to commence before the IM's notification, as operators only initiate the migration process in anticipation of increased operating costs associated with dual-mode rolling stock. Both older and recent surveys (Chapter 3.3) show that **operators lack** intrinsic **motivation**. For the dual-terminal scenario, which is more demanding and time-critical for transport operators, incentives must therefore be in place from the outset to make participation in the migration process advantageous. Such incentives must take the form not only of financial support but also of pilot projects for testing installed FRMCs on-board equipment, which is a prerequisite for its timely approval.

- **The availability of the necessary components** on the market will vary between infrastructure and vehicles. Although joint prototyping and testing form part of the standard's development, vehicle equipment manufacturers who have not participated in these campaigns may fall behind in terms of the required volume of hardware production, the development of software for the relevant functions, and its approval. The conditions for installation in vehicles are far more varied, the number of stakeholders and prototypes requiring approval is far higher, and the process is significantly longer. The risk of approved solutions being unavailable is therefore higher for transport operators than for infrastructure managers. From this perspective, **the scenario involving dual terminals**, in which transport operators initiate the migration process, is, at the very least, **highly risky** for them.

- Both scenarios allow for **a** partial **overlap** in the timing **of vehicle and infrastructure migration**, which may slightly shorten the entire migration process and, for example, achieve savings on the significantly rising operating costs of the GSM-R system being replaced. However, the proportion of vehicles supporting (using) this method of communication is significantly higher than the proportion of the network on which this communication is supported (used). The ratios shown in Table 8 are derived from a network model based on a graph of random paths of varying lengths; examples of the calculation tables are provided in Annex 2 of the study.

- The dual-infrastructure scenario is heavily dependent on the actual feasibility **of GSM-R and FRMCS coexisting in the 900 MHz band** (section 2.1.3), which has not yet been definitively verified. Both options restrict the band to a certain extent, and thus also the transmission capacity of the GSM-R network; to optimise this, they require gradual frequency reallocation during the migration. This entails **risks** of insufficient GSM-R capacity for the remaining vehicles using this standard, as well as risks of errors and subsequent operational disruptions during system configuration changes. From this perspective, the safer option involving the deployment of FRMCS in the 1900 MHz band (or in other bands under consideration) is more demanding in terms of modifications to the passive infrastructure, which will be necessary in the Czech Republic (Chapter 2.2), and also depends on the timely allocation of the relevant band for railway use.

- Another important consideration is the possibility **of coexistence between the two systems in terms of their placement** on rolling stock or on infrastructure masts (gNB). In both cases, these are spatial issues (space being occupied by existing antenna systems that are not always used efficiently), which prevent the necessary signal level separation between the systems in question and require additional selectivity measures; in the case of infrastructure masts, there are also issues of static load-bearing capacity, particularly when large surfaces of multi-element radiators are subjected to wind loads. Whilst the problems with masts can be resolved by replacing them – at the cost of increased investment and prolonged construction – this option is very often not available for vehicles either

- Estimates of a possible start date for the migration vary, due to the unclear timelines for the completion of FRMCS standardisation (at least up to Baseline 1 (V3)) and the subsequent commercial availability of components, ranging from 2029 (prepared investment plan) to 2032 (pessimistic scenario in the ERA's recommendations). Although national pilot projects are theoretically planned to run in parallel with the pan-European MORANE 2 testing from 2025 [37], they are only realistic within this timeframe, as neither national pilot projects on the required scale nor prototypes converted for MORANE 2 will be available for the period prior to V3, let alone the mass production of FRMCS components. The timetables for the technical preparation of network migration will therefore be very tight, with all the associated risks.

- **The** current **standardisation process**, carried out under considerable time pressure and resulting in a limited scope for future FRMCS V3 standards, carries the risk that subsequent versions of FRMCS will not be backwards compatible, and during the migration period (2027–

2050), the situation that arose during the introduction of ETCS may recur, whereby BL2 equipment installed on rolling stock prior to 2020 must be upgraded to BL3 by 2030, resulting in a service life of 13 years or less.

Table 8 compares the significance of some of these factors, or threshold values, for both main scenarios:

Table 8 – Main difference between theoretical migration scenarios

	Dual-infrastructure scenario	Dual-terminal scenario
Time buffers for notification of the end of GSM-R operation in accordance with the CCS TSI	greater	small to none
Availability of FRMCS components on the market	more important for the IM	critical for operators
Overlap between vehicle and infrastructure migration (migrated portion)	>69% of the network for 20% of vehicles	>66% of vehicles with 20% of the network
Impact of restrictions on GSM-R and FRMCS coexistence in the 900 MHz band	significant	minimal (without long-term coexistence)
Restrictions on system coexistence in terms of location	risk of having to replace gNB masts due to insufficient space and load-bearing capacity	often insurmountable space constraints on the vehicle roof

In terms of overall **scenario preferences**, both source [2] and the discussions held within this study's working group reveal **a** clear **effort** on the part of **IMs and transport operators to shift the current operation of both technologies to the other side** – whilst the only clearly articulated preference on the part of transport operators was a scenario involving the overlap of both systems on the infrastructure, 45 per cent of European IM respondents in the survey favoured a migration scenario utilising dual terminals, or a mixed scenario for special conditions. In the Czech Republic, both SŽ and the Ministry of Transport currently prefer the option of a one-off rapid transition to FRMCS (i.e. the option involving the widespread installation of dual terminals on vehicles). However, a current analysis suggests that **the dual-terminal scenario** – which is more time-consuming for transport operators and critical in terms of component availability and the approval of vehicle modifications – is **likely to be unfeasible within the required timeframe**, whilst the main risk for dual infrastructure is merely the coexistence of both systems in the 900 MHz band.

3.2 Migration plans of specific entities

Of the available sources, only **the DB InfraGO migration plan** [1] is sufficiently detailed. In the baseline scenario, GSM-R is the key safety-critical communication system (ETCS) at DB InfraGO and provides operational voice communication for vehicles with base stations (BS) spaced on average 7.6 km apart, one control centre per 9.2 km of track, one vehicle radio terminal (cab radio or EDOR) and 2.5 handheld terminals (HHTs) per 1 km of track.

DB InfraGO's seven-step migration plan envisages migration on a line-by-line and application-by-application basis, which requires the parallel operation of the GSM-R and FRMCS systems for a certain period **and dual equipment on vehicles** for both GSM-R and FRMCS.

- The plan begins with isolated pilot operations on lines currently equipped with analogue radio (1 location, specifically the SRCC test track on the border between Saxony and the Czech Republic), where the infrastructure, vehicle equipment and operational models will be tested together. This will be followed by live operation on regional lines (2 locations), where more operators will be involved and the processes of planning, construction and operation of FRMCS components, as well as railway operations themselves in this environment, will be optimised.
- The next steps will involve the deployment of FRMCS in parallel with GSM-R, initially on regional lines (1 location) and later on main lines (2 locations), where the interaction between FRMCS and GSM-R and the corresponding operational procedures will be tested and optimised. On the main lines, additional factors such as higher traffic density, the presence of multiple operators and high speeds will come into play.
- Subsequent steps will involve expansion beyond the boundaries of the DB InfraGO network, initially across individual border crossings, which have so far been operated under GSM-R. This will raise issues regarding cooperation with foreign railway administrations and national transport authorities, including international roaming and operational procedures for FRMCS networks and users. The plan for this stage also includes the first deployment of ATO GoA2.
- The seventh and final step involves the gradual live migration of individual lines using the procedures refined in the previous steps.

The parallel operation of systems (and the associated costs) is to be reduced as quickly as possible (again, on a line-by-line basis) where feasible, and efforts will be made to realise the benefits of FRMCS operation for both infrastructure managers and operators as soon as possible. The timing of individual activities during the preparation, construction and transition to FRMCS operation is expected to be as follows:

- **The development and testing of prototypes** in manufacturers' laboratories and on a dedicated test track (Digitales Testfeld Bahn) are already underway, independently of the CCS TSI 2023, and are scheduled to continue until early 2026.

- **The design, approval, planning and construction of** the core network and pilot lines will follow immediately upon the publication of the TSI CCS (September 2023), with completion scheduled for the end of 2028. This also includes preparations for widespread deployment. Pilot operations are expected to take place between 2027 and 2028, following the publication of the CCS TSI 2026 (FRMCS V3 standards).
- The pilot phase and roll-out of the DB InfraGO network are set to begin **with site preparation** (2024–2025); this, together with the completion of prototype testing, will be followed by **the implementation of the core network and its services**, **and the equipping of the pilot lines**, both of which are again scheduled for completion by the end of 2028. Together with the previous point, this constitutes **Phase 1 of** the DB InfraGO migration plan.
- Following the publication of the CCS TSI 2026 (FRMCS V3 standards), the planned widespread roll-out of FRMCS will also commence, and the five-year period for the implementation of FRMCS by operators (on rolling stock) will begin.
- **The** actual **migration period** of parallel operation of FRMCS and GSM-R follows the successful completion of the pilot operations (planned for 2029 – 2035). As part of this, once the preparation period for transport operators has elapsed, **the** gradual **phasing out of the GSM-R network** will commence (planned for 2032–2035)

The DB InfraGO plan provides for the integration of mobile network operators' (MNO) networks for backup purposes, similar to the arrangement currently provided by the GSM-P communications environment.

Norway also envisages a similar arrangement in its migration plan, drawn up jointly by the Norwegian Railway Directorate (Jernbanedirektoratet – a ministerial advisory body responsible for long-term planning and coordination of the sector) and the national infrastructure manager Bane NOR. The cost of this option for the Norwegian network, comprising 11,000 km of track and 8,000 existing GSM-R terminals, is estimated at €85 million.

Similarly, **the plan by the French SNCF Réseau** [36] envisages the replacement of GSM-R by as early as 2035

- across at least 97 per cent of its TEN-T network on its own infrastructure in the RMR bands, where it expects, in particular, higher availability of connections for ETCS L2 and for the regional rail network using FRMCS in the MNO bands,
- with the migration to be carried out between 2032 and 2035 via a one-off (theoretically during a night-time closure) switchover by control centre region (6 regions) in 2–3 stages, i.e. in **the extreme form of the dual-terminal scenario**. This presupposes the retrofitting of a significant proportion of rolling stock within a short period of 3–6 years.

3.3 Motivations of the stakeholders

As early as 2015, Study [2] sought to map the motivations that would drive migration among the main stakeholders representing rail operations – infrastructure managers (IMs) and operators. However, the study's informative value was limited, particularly on the part of operators, due to the low number of survey respondents from whom these motivations were elicited.

The motivations of entities **in the railway sector in the Czech Republic** were mapped in this study using a questionnaire with a similar structure. The main difference was that, instead of the introduction of GSM-R, past migration projects were represented by the introduction of ETCS L2, which had taken place more recently than the period under study and was perceived in preliminary consultations as a far more representative example of a migration project. Furthermore, unlike the original study, the evaluation of responses distinguished between passenger and freight operators, whose business conditions and financing methods in the Czech Republic are diametrically opposed; it can therefore be assumed that their perspectives on the economics of any technical changes, including the introduction of FRMCS, will differ fundamentally.

The results, represented by the average rating of the strength of motivation on a scale from 1 (marginal) to 5 (most important), are summarised in the table for the original sample of respondents (Europe) and for the entities surveyed as part of this study (the Czech Republic). The values shown in brackets were either highly variable among respondents or were mentioned only rarely and are therefore not representative:

Table 9 – Possible motivations for IMs and transport operators to switch to FRMCS

	infrastructure managers (IM)		Operators	
Motivation aspect	**Europe**	**Czech Republic**	**Europe**	**Czech Republic**
Degradation of the reliability of the installed equipment base	(2)	3	(2.5)	(1.0)
Increase in maintenance costs	(3)	2	(2.5)	0.5
Prospects for cost reduction	(3)	-	(2.5)	-
Potential for introducing new services and applications	3	3	(3)	(2.5)
End of the life cycle of key technologies (specifically GSM-R)	4.5	2	(2.5)	2.5
EU regulation	4	4	4.5	5
Link to other projects – construction of new lines, procurement of rolling stock, introduction of ETCS, etc.	4	2	(3)	0.5

Motivation aspect	infrastructure managers (IM) Europe	infrastructure managers (IM) Czech Republic	carriers Europe	carriers Czech Republic
Standardisation and commercial availability of new products	(1.5)	2	-	-
Other reasons, such as • national requirements • replacement of network infrastructure	(0.5)	-	(1.5)	-

The individual motivating factors can be assessed in more detail as follows:

- **The deterioration in the reliability of the installed equipment base,** even with regular maintenance, will eventually necessitate its physical replacement, which may present an opportunity to transition to successor technology. However, in Europe, this motivation is perceived as unimportant by both infrastructure managers and operators; in the Czech Republic, infrastructure managers perceive it as less important than operators do.

- **The rise in maintenance costs,** as a motivating factor, coincides with concerns regarding the end of support for GSM/GSM-R. In addition to growing difficulties in sourcing spare parts, this also includes the gradual decline in the number of specialists in 2G technology capable of maintaining it. As a motivating factor, this is moderate or uncertain; for Czech rail operators, it is minimal, as even the reported cost figures are strikingly low compared with those in Europe.

- **The prospect of cost reduction** varies across Europe depending on the type of organisation: whilst infrastructure managers (IMs) expect lower **maintenance** costs for the successor technology than for GSM-R, transport operators are hoping for lower **acquisition costs**. In principle, cost reductions for IMs also include the possibility of sharing (concurrently developed) 4G/5G networks for critical communications, intended for emergency and security services (PPDR). In the Czech Republic, this motivation is completely absent on both sides.

- **The potential for introducing new services and applications** is viewed, both in Europe and in the Czech Republic, as a moderate motivation, typically in terms of the potential for better (faster) communication services, enabling infrastructure managers to achieve higher operational utilisation of the line; new applications that will lead to a significant reduction in operating costs; or as an opportunity for services and applications that cannot be operated on GSM-R. However, the only more specific examples cited are the migration of (critical) ATO and (performance-related) TCMS, diagnostics, etc., from the currently sole available MNO communication system to FRMCS; other potential benefits are already concealed under the vague slogan ‘desirable railway digitalisation’ [1]. The anticipated applications are, for the most part, non-critical. Neither transport operators nor service procurers are motivated to deploy critical applications addressing safety; they are merely compelled to do so by legislation and the authorities responsible for its enforcement. For passenger transport operators, this also includes an interest in providing new broadband services and passenger services, though these fall outside the scope of this study. For various reasons, some of these applications are already being operated by larger and/or passenger transport operators using 4G LTE MNO technology. Smaller transport operators lack this motivation, as the IT investments associated with such applications are not cost-effective for them; given their smaller scale of operations, it is more cost-effective for them to continue using older methods of process management without IT support. Furthermore, whilst FRMCS for these applications will ensure above-standard communication quality, it will not result in cheaper operation; nor, in its early stages, will it provide sufficient capacity, even within the RMR bands (see Chapter 2.6). The findings of our own survey on this point are discussed in more detail in Chapter 1.1.

- **The end of the life cycle of key technologies (specifically GSM-R)** will, from the IM’s perspective, significantly increase operating costs and essentially prevent further network development (deployment on additional lines). From a temporal perspective, it marks the end of the anticipated migration period. **For European IMs**, **this is clearly the leading motivation**; for some authorities, this is reinforced by the expected end of GSM (2/2.5G) operations by public operators, from whom they use roaming in areas with sparse railway coverage or as a backup communication system. In the Czech Republic, this is perceived as a weaker motivation, particularly among IMs.

- **Regulation by the EU** has been and continues to be perceived primarily as a legal obligation to implement the new system. It was **the only motivation consistently rated highly** by all surveyed entities – both IMs and transport operators – both at European level and in the Czech Republic. In practice, this manifests as **legislative requirements passed** on by IMs to transport operators, who face the risk of restrictions on the interoperability of their rolling stock, accompanied by a loss of revenue, a decline in operational efficiency, or potentially penalties. A more detailed study [5GBB-D] has already confirmed that, under these conditions, it is not possible, for example, to quantify the benefits using standard CBA methods.

- **The interdependence with other projects,** specifically the roll-out of ETCS L2, presents European IMs not only with the absence of a suitable radio carrier but also with the inadequacy (in terms of capacity and functionality) of the existing GSM-R installation. In this case, upgrading to the successor technology is a viable solution. For European operators, a single concern prevails on this point – guarantees that newly installed technologies on rolling stock, particularly on newly acquired vehicles, will not need to be replaced again within a reasonable timeframe. Stakeholders in the Czech Republic initially reported this motivational factor as weaker than the European average; however, issues **relating to the integration of communication technology with ETCS** and negative experiences with changes to installed technology – even on newly acquired rolling stock – ultimately **proved to be key factors** in the discussions.

- **Standardisation and the commercial availability of new products** are low motivators both on a European scale and in the Czech Republic; for operators, they are non-existent. At least for operators in the Czech Republic, this is again due to negative experiences from past instances of technology migration, such as the transitions from national Class B radio systems to GSM-R or to ETCS safety-critical operation in exclusive mode. In addition to the implementation and funding issues described below, there were various national approaches and specific circumstances (e.g. resulting from the priority deployment of GSM-R in border sections following more extensive roll-out in the neighbouring network), which led to implementations that were not fully interoperable and to restrictions on the cross-border operation of rolling stock.

Although respondents to the survey conducted as part of this study did not explicitly mention ‘other’ sources of motivation for the transition to FRMCS, in open discussion they cited several recurring factors **that were particularly demotivating for operators** regarding the technological change under study, factors also confirmed by **an** earlier **joint analysis by DB and SNCF** from [1]:

- **The vehicle approval process** – on the one hand, complex and administratively and financially demanding; on the other hand, undermined by pressures to shorten and formalise verification runs, the results of which are then not representative and do not guarantee interoperability. The joint analysis by DB and SNCF in [1] did suggest a solution involving the independent readiness of hardware and software for FRMCS, whereby FRMCS-compatible hardware would be available so that vehicles could be fitted in advance, with only software upgrades being implemented during the live migration, thereby extending the migration period for operators. However, a prerequisite for such an approach is that software modifications can be carried out on vehicles without the need for recertification, which, at least in the Czech context, appears to be unrealistic. Another question is to what extent hardware modifications (at least the modernisation of cabling, passive components and mechanical parts, etc.) will be hindered by the possible incompleteness of the FRMVS specifications, even in V2 and V3.

- **The** de facto **monopoly held by manufacturers** of railway-specific technologies and the dependence of the process – including certification – on the vehicle manufacturer, who can effectively block retrofits, particularly of small batches of older vehicles in which they have no (commercial) interest. At the same time, the integration of new technologies is demanding during the installation phase and requires vehicle modifications, particularly for older vehicles. The slow product innovation cycle (exceeding 7 years), or even a complete halt to innovation, is compounded by **limited** design **capacities**, workshops and test facilities, which are likely to be insufficient for the large anticipated volume of work in the short term (2029–2035, with the first GSM-R roll-backs from service during 2032) whilst migration is taking place across virtually all European railways (approximately 10,000 vehicles per year). All these factors will result in **prices that are significantly higher** than those for comparable commodity technologies and the associated servicing, making the transition to the new technology economically unviable.

- **The lack of secured funding** for the relatively large investments required, particularly on the part of transport operators, is confirmed by the findings [1]. In the experience of transport operators in the Czech Republic, the **financial support mechanisms** designed to address this problem are **inadequate**; they fail to motivate transport operators because, for various reasons, the actual level of support falls short of the indicated level. One of the causes is the constant change in requirements and regulations, whereby the customer is unable to specify a requirement or the supplier does not have a finished product. This results in deliveries being split into stages, with the later stages no longer eligible for financial support, and the actual proportion of support relative to costs falling from the entitled 80 per cent to, for example, as low as 50 per cent. Yet the level of support is crucial for economic viability, as realistic financing methods force transport operators to pass on these unavoidable costs through higher service charges, which puts them at a competitive disadvantage – in freight transport, this generally results in an undesirable shift of customers to road transport; in passenger transport, it leads to the loss of contracts with public transport service providers.

The current TSI CCS 2023 similarly mandates **a forced transition to System Version 3.0 (Baseline 4),** introduced as the first FRMCS-compatible version, which, however, also alters safety functions. At the same time, its commercial availability is not expected before 2032, by which time the number of vehicles in operation or being delivered that support older versions (predominantly BL 3 by 2032) will have grown. The volume of vehicles requiring an upgrade may then prove unmanageable during that period. For transport operators in particular, the TSI CCS 2023 alternatives—which involve a significantly smaller scope of recertification—would therefore be far more acceptable: a solution using an additional functional block for the existing ETCS BL 3 (**the** so-called FRMCS **adapter**) or **the** so-called **‘light’ version**, which implements the Coordinating Function and the FRMCS Communication Function in accordance with the TSI CCS 2023 specification, but does not alter the safety functions, and the ETCS application itself remains BL 3 (SV 2.1).

3.4 Detailed migration procedure in the Czech Republic

As in the case of railway operations support applications in Chapter 1.1 of the Strategic Document ‘National ERTMS Implementation Plan’ [26], there is no detailed plan or timeframe for the transition to FRMCS; however, there is a working document from Správa železnic, s.o., made available within the working group preparing the study, covering roughly the period 2020–2040 and assuming a 10-year period of parallel migration of both infrastructure and rolling stock. Based on the results
[25] and discussions within the working group, the initial conditions on the main lines of the Czech Republic can be characterised as follows:

- Migration carried out solely in the 900 MHz band (Chapter 2.1.3) is generally considered technically feasible, although the results of the analysis of communication requirements do not suggest a long-term outlook for this approach. For this option, according to [25], Part C, the same coverage is anticipated as for the existing GSM-R system, with an average gNB distance (at track stations) of 3.9 km within the network (based on data provided by SŽ in the survey), or up to 5.8 km on flat sections of main lines [25], Part C.

- Given the parallel development of MNO signal coverage along the lines for commercial applications, which utilise the 800 MHz (n20) and 1800 MHz (n3) bands, the passive infrastructure (masts, power supply connections, IP transmission and communication environment) is already partially prepared for the potential deployment of FRMCS in the 1900 MHz band, provided that the IM and MNO bands are shared. The decisive factors here are the spatial and load conditions of the masts, ensuring the installation of new antenna systems at the required height, with sufficient wind-exposed area (to account for random mast loads) and spatial separation between antennas for the necessary shielding (for RMR bands, at least 2 m vertically under various requirements [24] [6]). It is likely that not all masts will meet these conditions (study [25], for example, anticipates the need to raise masts at approximately one-third of existing sites, which effectively means replacing them).

- A shortcoming of the existing passive infrastructure is the exhausted capacity of the SŽ optical cable network, which will require renewal; the costs of this were not factored into the cited models and will need to be included in the costs of passive infrastructure modifications under the item ‘optical connections with a branch from the DOK over distances of hundreds of metres’.

- For the Czech Republic, compared with other countries, there is a far stronger link between the planned FRMCS migration and the migration already underway between different ETCS BLs. **Transport operators' historical experience** with technology migration projects has been **poor**, **and** a prime example of a mismanaged long-term (essentially permanent) migration in the past was, and remains, the introduction of ETCS in place of the national LS signalling system. The motivation in this case was clearly solely the requirement of the Infrastructure Manager (IM), with no visible benefits for transport operators. This ambitious plan, implemented up to 10 years ahead of other countries, was accompanied by constant changes to regulations, rules and requirements (ETCS Baseline) during implementation, as well as the unavailability of the target technologies, products and services on the market. Whilst initially only the commercially available Baseline 2 could be deployed, after 2021 there was pressure to upgrade all rolling stock to Baseline 3. Smaller operators in particular, with small numbers of vehicles in individual series or operating older rolling stock, encountered a lack of interest from suppliers in such retrofit projects, as well as the imposition of unrealistic deadlines for the procurement of necessary components, installation, user training and other steps required for commissioning, which resulted in enormous costs. As a result of an unclear and, ultimately, unfulfilled financial support policy, these costs remained uncovered, as the actual amount of support was ultimately significantly lower than expected.

Table 10 compares various characteristics and cost items of both theoretical variants using a model with parameters that most closely approximate the situation in the Czech Republic, as revealed by the questionnaire survey. To quantify the costs, the economic model from study [2] was again used; however, this model employed certain simplifications that are no longer acceptable. The model was therefore modified in detail for the purposes of this study to better reflect the reality of the specific network:

- The original model assumed full GSM-R network coverage and a 1:1 migration ratio, which will not be achieved in the case of the Czech Republic. In such a scenario, OPEX remained stable during the initial stages of the migration, whilst investment was limited to simple technology renewal amounting to just a few per cent. The modified model assumes partial coverage and the gradual expansion of the GSM-R network by the infrastructure manager (IM) in accordance with the original development plans, right up until the start of FRMCS network construction.

- The original model did not account for investment in the passive part of the infrastructure, which was to be reused unchanged for the upcoming FRMCS technology. As a result, the scenarios studied were limited to the replacement of GSM-R in the 900 MHz band, where coverage provided by the old and new radio technologies does not differ significantly (see Section 2.1). Under the specific conditions of this study, this assumption is not met, not least because one of the variants studied involves the deployment of the 1900 MHz band with a different cell structure (smaller ISDs), requiring the passive infrastructure to be expanded by tens of per cent. The model has therefore been modified to include passive infrastructure as a separate component, with specified amounts for capital expenditure (CAPEX) and operating expenditure (OPEX).

- The original model did not factor in the replacement of GSM-R equipment by operators due to the end of its service life. The modified model includes this replacement in the operator's operating costs until the start of the campaign to replace on-board equipment with dual-mode and/or FRMCS-compatible units. Similarly, it did not index the operating costs of GSM-R rolling stock equipment to the progressive increase in GSM-R prices towards the end of its support period. The modified model also includes this progression in the operators' OPEX for the reasons set out in section 3.3.

- Due to the strong link between the FRMCS and ETCS migration projects mentioned above, the scenario also quantifies the costs of a mandatory ETCS upgrade; in all scenarios, this is associated with the installation of FRMCS (at a minimum, support for the Coordinating function and the communication stack in accordance with UNISIG Subset 037-3), Based on experience with the production of ETCS components to date, such an upgrade is included in the scenario involving dual terminals and, on several occasions, in parallel with the infrastructure's transition to FRMCS, when shortcomings in the early production of ETCS BL4 – which were not detected during the preparatory phases – are expected to require further modifications.

- Data provided by SŽ has shown that the infrastructure construction costs in the original study [2] are significantly underestimated by Czech standards. The model therefore uses values derived from the per-kilometre investment costs for new GSM-R construction – civil engineering works / passive infrastructure 40 per cent, and retrofitting FRMCS to existing passive infrastructure 72 per cent – as used in budgets via the SPOŽES tool.

- Following experience with the implementation of ETCS, the migration period for both infrastructure managers and operators in the scenarios has been extended compared with the original model to a much more realistic 10 years. The second phase of migration therefore falls, in all scenarios, **within the period following the announced end of GSM-R support**, which is reflected here by a 100% increase in all costs for its renewal and maintenance, with the risk that over such a long period (the obsolescence of the communication technology exceeds 50 years!) **the rise in costs** will be **even greater**.

- The model uses more up-to-date values for the Czech economy regarding inflation (2 per cent) and the discount rate (4.25 per cent).

Detailed model inputs, including model prices for components and operating cost items, are set out in Annex 2 of the study. The outputs of such a simple model are for guidance only; for a more accurate comparison of the options specified in subsequent stages of migration preparation, it will be necessary to carry out a comprehensive cost-benefit analysis (CBA) and a more detailed analysis of technical risks.

Table 10 – Model economic comparison of migration approaches

Migration scenario	A (dual infrastructure)	B (dual terminal)	C (1900 MHz overlap)	D (interoperability issues)
Total length of lines equipped with GSM-R at the start of the scenario	2,269 km	2,269 km	2,269 km	2,269 km
Target length of lines with FRMCS installed	2,569 km	2,569 km	2,569 km	2,569 km
Number of vehicles fitted with a GSM-R voice terminal (cab radio)	4,370	4,370	4,370	4,370
Number of vehicles fitted with EDOR for ETCS	2,190	2,190	2,190	2,190
Proportion of passive infrastructure requiring replacement or upgrading due to the deployment of FRMCS	5 %	5 %	61 %	5 %
Completion of the construction and renewal of the GSM-R system on the infrastructure	2050	2039	2050	2039
Deployment of the FRMCS system on the infrastructure during the period	2030–2040	2040–2050	2030–2040	2040–2050
Campaign to retrofit vehicles with FRMCS equipment	2040–2050	2030–2040	2040–2050	2030–2040
GSM-R operation on infrastructure by	2050	2040–2050	2050	2040–2050
IM investment in FRMCS (years x billion CZK/year)	11 × 0.75 billion CZK	11 × 0.94 billion CZK	11 × 0.96 billion CZK	11 × 0.94 billion CZK
Related IM investment in ETCS (years x billion CZK/year)	11 × 0.69 billion CZK	11 × 0.84 billion CZK	11 × 0.69 billion CZK	11 x 0.84 billion CZK
Carriers' investment in FRMCS (years x billion CZK/year)	11 × 0.27 billion CZK	11 × 0.22 billion CZK	11 × 0.27 billion CZK	21 × 0.26 billion CZK
Related investments by transport operators in ETCS (years x billion CZK/year)	11 x 3.0 billion CZK	11 x 2.5 billion CZK	11 x 3.0 billion CZK	11 × 2.5 billion CZK
Operating costs of the infrastructure manager included in the model for the period under review (including necessary GSM-R renewal)	CZK 24 billion	CZK 12 billion	CZK 24 billion	CZK 12 billion
Total costs at current prices (NPV) for the period 2025–2050 (IM and operators)	CZK 51 billion	CZK 43 billion	CZK 52 billion	CZK 47 billion

All the quantified scenarios assume that the migration will take place during the same period, 2030–2050, which has been chosen so that, according to current assumptions, the components required for the migration will already be available on the market and the period will be sufficiently long to allow the migration to be carried out by transport operators and on the infrastructure without any overlap. Parameters such as vehicle specifications, expected service lives and component prices are the same for all scenarios. Total costs at current prices (NPV) are calculated for the period 2025–2050; outside this period, the scenarios do not differ in substance. CAPEX and OPEX figures are calculated at current prices, applying a constant inflation rate throughout the entire period under review. Furthermore, a discount rate – also constant throughout the period under review – is factored into the NPV values.

- **Option A** represents a **migration** scenario **with dual infrastructure**. Two immediately consecutive 11-year intervals are planned for the installation of technology in the infrastructure (step 1) and for the retrofitting of rolling stock (step 3). IM's investment in GSM-R technology is completed by 2029, but operations—burdened by rising costs, including the necessary renewal of full coverage—continue until 2050. The newly constructed network is used solely for testing purposes until its completion and is operated at minimal cost. The renewal of GSM-R technology by transport operators ends in 2039, when its total costs also peak at a level half that of subsequent investments in FRMCS; they then fall to the level of routine maintenance and gradually disappear as this technology is phased out of rolling stock. From an NPV perspective, this option is more expensive than the option with dual terminals; the difference is mainly due to the costs of maintaining and renewing GSM-R on the infrastructure manager's side.

- **Option B** represents a scenario **utilising dual terminals**. For equipping rolling stock (step 1) and for installing the technology in the infrastructure (step 3), two immediately consecutive 11-year intervals are again planned. IM investment in development

Although the roll-out of GSM-R technology will be completed by 2029, operations will continue until 2050; however, from 2039 onwards, operating costs will fall as the renewal of GSM-R ceases and the system is subsequently phased out on sections where it is replaced by FRMCS. The renewal of GSM-R technology by transport operators ends as early as 2029, and its remaining operating costs from 2036 onwards will fall until its decommissioning in 2040. The investment requirements for the infrastructure manager (IM) are higher than in the previous option, but for rail operators (assuming financial support for them, which also represents a need for public funding) they are significantly lower; furthermore, the total costs for the IM and rail operators, expressed in net present value (NPV), are minimal in this option. As with all variants, **the decisive cost item is the operators' investment in the required ETCS modifications**, followed by the IM's costs associated with maintaining GSM-R operations.

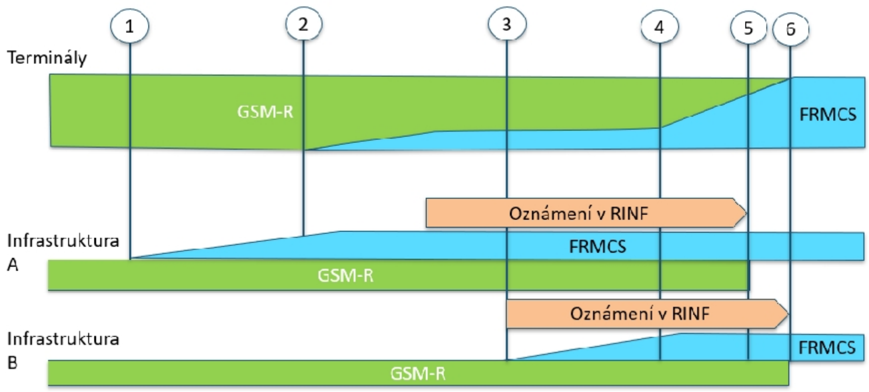
- **Option C** involves the deployment **of FRMCS in the 1900 MHz band** with the creation **of a dual infrastructure**, whereby the GSM-R network continues to operate in the 900 MHz band without change. The deployment of the 1900 MHz band, in addition to the replacement of certain parts of the passive infrastructure, involves a 56 per cent increase in the number of gNBs (the maximum value, determined by an analysis of the results of study [25] – see Section 2.2.1 – although this will not need to be adhered to at the start of operations – see Section 2.6) to achieve the necessary reduction in cell ISD. Other costs relating to vehicle and infrastructure equipment are assumed to be the same as for Option A in the 900 MHz band, due to a lack of more precise data. The model's results then confirm that this change in passive infrastructure represents the main difference – an increase of approximately CZK 2 billion in IM investment (in the total NPV of the migration, due to the high discount rate applied, amounting to CZK 1 billion).

- **Option D** again represents a scenario **utilising dual terminals,** but this time in the event that the implementation specifications are not finalised or that versions fully interoperable with the infrastructure or the current ETCS BL are not available for installation on rolling stock. From the IM's perspective, this option is identical to Option A, and the associated investment by operators in ETCS modifications is also the same; however, based on experience with ETCS, the deployment of non-fully interoperable versions of FRMCS on-board equipment will require continued investment in rolling stock components throughout the 21-year migration period, representing an additional cost of 2.5 billion CZK for transport operators. Despite this increase, however, Scenario D is still more advantageous in terms of total NPV than the technically more feasible (see Section 3.1) dual-infrastructure scenario. The model's results **confirm the operators' view** that the stability of specifications and **full interoperability of** FRMCS **components** with one another, and **particularly with ETCS**, **is key** to keeping migration costs within reasonable limits. A scenario involving modifications to ETCS installations would be far less favourable than the one quantified here, due to the ratio of FRMCS to ETCS costs.

3.5 Timing of the transition from GSM-R

The study [2] also included scenarios involving multiple (neighbouring) countries with different timelines for migration to FRMCS. The variants are again based on the basic division into an approach with system overlap on the infrastructure and the use of dual terminals, as described in Section 3.1. The **migration** process **with dual infrastructure** in two interconnected networks involves the following steps (where, unlike in the cited study, 'IM A' denotes the network initiating the migration and 'IM B' the delayed network, regardless of their size):

Figure 4 – Migration scenario for two networks with dual infrastructure



1: Initial phase
The infrastructure and operators of both networks are currently using GSM-R. IM A is building the FRMCS system in advance, whilst the operators are carrying out commercial and technical preparations for the migration (selection of suppliers, testing and approval of prototypes using sections of the FRMCS infrastructure built by IM A).

2: IM A commissions the FRMCS system on a significant part of its infrastructure. Operators are commencing the mass retrofitting of their rolling stock (and other communication terminals) to the FRMCS system, but only for those parts using solely Network A's infrastructure, as the modernised rolling stock no longer supports GSM-R and thus loses interoperability with Network B. Operators **are** therefore **waiting for** the migration on Network B to commence for a significant portion of their rolling stock. However, the GSM-R infrastructure on Network A also remains in operation to accommodate vehicles transitioning to and from Network B, albeit at the expense of IM A. This OPEX is gradually increasing as support for GSM-R comes to an end. At some point during this phase, IM A announces the date for the cessation of GSM-R operations in accordance with TSI CCS Annex I §7.3.1.2.

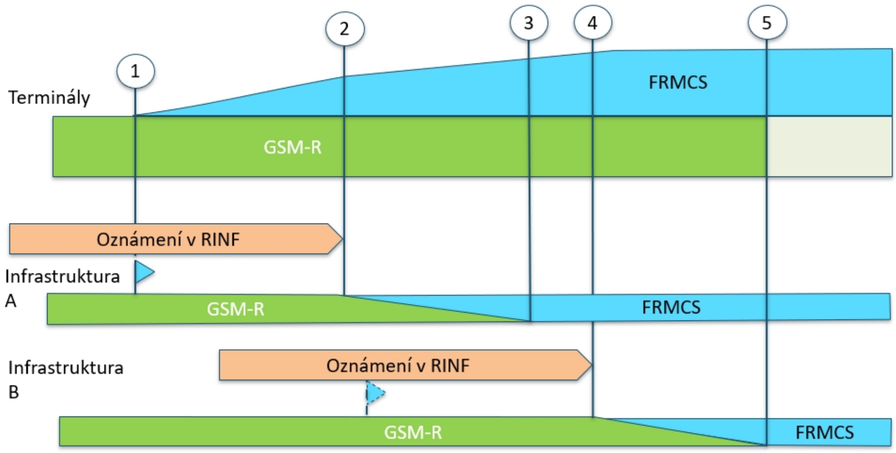
3: IM B is deploying the FRMCS system and, no later than during this step, announces the date for the cessation of GSM-R operations.

4: IM A commissions the FRMCS system on a significant part of its infrastructure, and operators may continue to upgrade the remaining rolling stock to FRMCS, which previously used only Network B infrastructure.

5: Rolling stock on Network B, operating on Network B's infrastructure, is upgraded, and IM A may cease GSM-R operations. 6: The migration of rolling stock is complete on Network B as well; therefore, its IM may cease GSM-R operations.

The steps for the procedure using **dual terminals** are, conversely, as follows:

Figure 5 – Migration scenario for two networks with dual terminals



1: Initial phase
Both the infrastructure manager and railway undertakings are using GSM-R in operation. In accordance with TSI CCS Annex I §7.3.1.2, IM A was required to announce, well in advance, the first dates for the cessation of GSM-R operations, which fall within step 2. Operators are retrofitting all rolling stock using infrastructure A with FRMCS-compatible terminals, or converting them to terminals supporting both technologies, in advance. During this phase, testing and type approval of the retrofitted vehicles must take place, for which the IM must provide the necessary conditions (pilot track section).

2: Commencement of of of
FRMCS. A significant proportion of vehicles using Infrastructure A are equipped for FRMCS operation, and IM A is building and gradually commissioning the FRMCS system. Operators continue to retrofit their rolling stock – but continue to use the GSM-R infrastructure on Network B. GSM-R OPEX, with support coming to an end, is increasing. IM B must also announce, well in advance, the first dates for the cessation of GSM-R operations, falling within Step 4, and, where necessary, provide pilot infrastructure for the testing and approval of rolling stock equipment.

3: IM A ceases GSM-R operations across the entire network and operators use FRMCS, for which their rolling stock is already equipped. GSM-R operations continue on infrastructure B, and its OPEX continues to rise.

4: Operators complete the fitting of FRMCS-compatible terminals on vehicles using exclusively Infrastructure B, whilst IM B gradually builds and commissions the FRMCS.

5: IM B has completed the construction and commissioning of FRMCS and has discontinued GSM-R operations across the entire network. GSM-R equipment on vehicles is no longer required, and its renewal and maintenance can be discontinued.

In addition to the conditions and risks discussed in section 3.1, cross-border operations introduce further risks:

- **Changes to specifications** during the migration period – which are highly likely given the current standardisation process – carry the risk that implementations in neighbouring networks will not be fully interoperable, even if only temporarily; migration in accordance with Network A's specifications will not guarantee compatibility with Network B. This could then lead to a repeat of the current situation, where vehicles are fitted with nationally specific subsystems or functions, or are upgraded in parallel with the installation of FRMCS on both infrastructures. Both of these approaches will increase the cost of vehicle migration and complicate the approval process.

- Elements **of national specificity** may be embedded within the harmonised standards themselves. A current example is the content of FRMCS profiles (the equivalent of GSM-R SIMs), which is planned separately on the vehicle for each network traversed and must be provided to that network's IM. The unclear situation regarding changes to and approval of profiles may severely restrict the interoperability of vehicles, at least in the early stages of migration.

- The migration process in a network migrating at a later stage **has a retroactive impact** on the process in a network migrating earlier. In a dual-infrastructure scenario, for example, a delay in migration within infrastructure B will halt the migration of operators' terminals in network A and consequently prolong the forced operation of GSM-R on infrastructure A. Conversely, the unilateral termination of GSM-R support on infrastructure A has an impact on operators on network B, resulting in increased migration costs or restrictions on their ability to switch to network A. To mitigate such effects, **coordination between IMs** would be necessary, for which there are as yet no appropriate tools.

- Another risk associated with a lack of international coordination is that different IMs may opt for **different migration approaches**. The approach involving dual terminals is safer in this respect, as the conditions for operators are essentially the same regardless of which scenario IM B chooses. Conversely, the combination of a scenario involving dual infrastructure on Network A and the requirement for dual terminals on Network B is critical. In such a case carriers on Network A may only retrofit vehicles intended for their own network, whilst the rest must be fitted with dual-system terminals, even though their network does not require it. The increased operating costs for IM A associated with running dual systems are thus partly negated.

- A common extreme case of both the aforementioned uncoordinated approaches is **countries that have no plans** whatsoever **to migrate to FRMCS**, e.g. European countries outside the EU. Operators wishing to operate on their networks will then have to extend GSM-R support – or even support for national Type B systems – on their vehicles indefinitely and, despite the technical problems discussed in section 2.1.3 and the approach taken by the IMs themselves, opt for multi-standard terminals.

Table 11 summarises the magnitude of these risks for both main scenarios

Table 11 – Significance of various risks for cross-border operation scenarios

	Scenario with dual infrastructure (on Network A)	Dual-terminal scenario
Changes to standards during the migration period	Increase the cost or delay migration for carriers	Do they make migration more expensive for transport operators?
Impact of the pace of migration on Network B	More sensitive; delays progress for both IMs and Network A carriers	Safer, increases only carriers' OPEX
Consequences of different types of migration in both networks	Risk of additional costs and delays for Network A carriers	Safer, does not depend on the choice of IM B

The scenario utilising dual terminals, although more costly, particularly for carriers, is in many respects less demanding in terms of coordination between the parties involved – for carriers in Network A, it provides essentially the same conditions regardless of which scenario IM B chooses, or over what timeframe. This difference between the two basic scenarios in terms of coordination requirements was also generally confirmed by the original study [2]. In real-world migration processes, a certain proportion of dual-mode vehicles being used is highly likely.

3.5.1 Model results

The main result of the simulations carried out in the study [2] was the quantification of expected costs at current prices (NPV) for all variants studied. For modelling purposes, the railway networks in the study were divided into three categories according to size. Despite the time lag and certain simplifying assumptions made initially (proportions of cross-border traffic, the same price level for all participants, the duration of migration periods, etc.), in addition to the conclusions presented directly in the cited study, further conclusions can be drawn from the calculated NPVs regarding the impact of the timing of migration to the FRMCS in various neighbouring networks on the costs borne by the participating IMs and operators:

- In the case **of a medium-sized network** migrating **later** than a neighbouring large network (the calculated scenario closely corresponds to that of Germany and the Czech Republic), the impact on the larger, earlier-migrating network was negligible (within ±5 per cent), whilst the increased costs are borne entirely by the smaller, later-migrating network (IM by >10 per cent, more pronounced in the case of migration with dual terminals, with carriers seeing an increase of around 20 %).
- In all cases, the percentage figures must be adjusted for the total increase in migration costs across two interconnected networks compared with two isolated migrations, which, depending on the specific scenario, amounts to 3–15 per cent. At the same time, the ratio of IM migration costs to those of carriers is several times higher (ranging from 5:1 to 10:1 depending on the variant), so the increase is generally attributable entirely to the IM.

To refine the results to reflect the current conditions of the Czech Republic's network, the model mentioned in Section 3.4 was used in a scenario incorporating cross-border operations into a network with a different migration timetable. As with the modelling of the situation in an isolated network, the model was updated in several respects:

- The original model assumed that the proportion of modernised vehicles during the concurrent implementation of FRMCS on vehicles and in the infrastructure was the same as the proportion of modernised infrastructure. More detailed network operation models show that this assumption is incorrect and that the proportion of vehicles communicating using a specific standard is always higher than the proportion of that standard in the infrastructure. Specific examples of these differences have already been given in Chapter 3.1.
- The original cross-border operation model quantified the expected costs for both networks under the simplifying assumption of identical price levels in both countries. A survey conducted as part of this study indicates that this assumption is incorrect. As it was not possible to obtain more specific data from other networks within the timeframe for preparing the study, the model was simplified so that it quantifies only the costs of a single network, namely the Czech network. As a result of this simplification, the model's results do not depend on the size of the foreign network; consequently, the discussion of variants with different ratios of network sizes—which is covered in some detail in reference [2]—is irrelevant here.

The modelling therefore focused on the economic assessment of the selected risks from Section 3.5. The results are presented in the following table in the same format as the results for the isolated network in Section 3.4:

Table 12 – Model-based economic comparison of selected migration approaches for two neighbouring networks

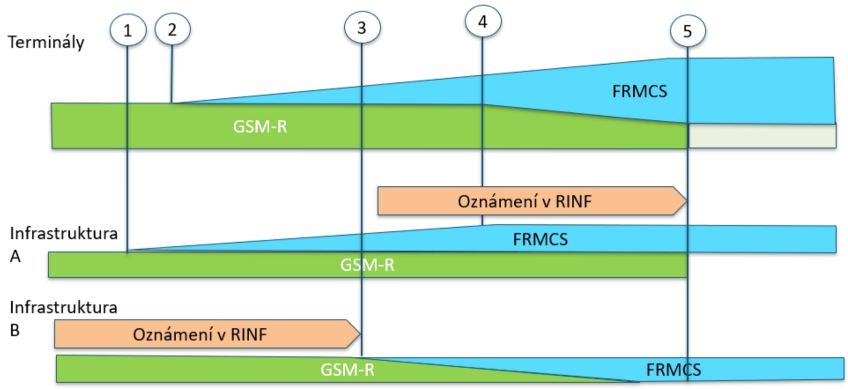
Migration scenario	**E (early migration)**	**F (later migration)**	**G (various migrations)**
For the total length of domestic lines equipped with GSM-R and FRMCS installations, the number of vehicles and the proportion of passive infrastructure renewal, see Table 10 in Section 3.4			
Completion of the construction and renewal of the GSM-R system on the company's own infrastructure	2050	2050	2050
Deployment of the FRMCS system on our own infrastructure during the period	2030–2040	2032–2042	2030–2040
Campaign to retrofit vehicles with FRMCS equipment	2040–2050	2042–2050	2037–2047
GSM-R operation on own infrastructure by	2050	2050	2050
Construction of the FRMCS system on the neighbouring network	2041–2046	2030–2035	2041–2048
End of GSM-R operations on the neighbouring network	after 2050	2045	2041–2048
IM investment in FRMCS (years x billion CZK/year)	11 × 0.77 billion CZK	11 × 0.8 billion CZK	11 × 0.77 billion CZK
Related IM investment in ETCS (years x billion CZK/year)	11 × 0.69 billion CZK	11 × 0.72 billion CZK	11 x 0.69 billion CZK
Carriers' investment in FRMCS (years x billion CZK/year)	9 × 0.32 billion CZK	9 × 0.35 billion CZK	11 × 0.25 billion CZK
Related investments by transport operators in ETCS (years x billion CZK/year)	9 × 3.7 billion CZK	9 x 3.9 billion CZK	11 x 2.9 billion CZK
Operating costs of the infrastructure manager (IM) included in the model for the period under review	CZK 24 billion	CZK 24 billion	CZK 24 billion
Total costs at current prices (NPV) for the period 2025–2040 (IM and transport operators)	CZK 50 billion	CZK 51 billion	CZK 51 billion

- **Option E** models the more likely approach expected from discussions, whereby **the migration of the Czech infrastructure** will commence **earlier** than in neighbouring countries. Among the various reasons for this is the need to limit subsequently underutilised investment in the GSM-R system, the planned completion of which currently overlaps with the anticipated migration period. This variant is based on a dual-infrastructure scenario, which previous analyses have shown to be more realistic and also more sensitive to various external influences. In this variant, the FRMCS infrastructure on Network B will not become operational until 2046; consequently, due to the transition to Network B, domestic operators can modernise only around 40 per cent of their rolling stock (unless they fit it with dual terminals) so that, by 2046, the necessary proportion of vehicles compatible with Network B infrastructure remains. This is modelled by a suspension of investment by operators in 2045–46, followed by an accelerated migration so that the re-equipment is completed by 2050, when GSM-R operations will cease on both networks. From the IM's perspective, this variant is cost-neutral compared to variant A in section 3.4. The results of this variant also account for the risk of a slowdown in the migration process in neighbouring networks, as even in that scenario, the commissioning of a significant portion of the FRMCS infrastructure on network B remains crucial.

- **Option F** models the opposite approach under the same conditions – **the Czech infrastructure** will be **migrated later** than that of neighbouring networks. Whilst the construction and commissioning of the FRMCS infrastructure on the home network will be delayed by two years compared with Option A in Section 3.4, full coverage of the neighbouring network will be achieved as early as 2035, and GSM-R operations on that network will cease as early as 2045. Operators will have to wait to install FRMCS whilst ensuring interoperability with the domestic network and, once it is fully operational, will need to upgrade their rolling stock swiftly so as not to restrict the interoperability of the portion of rolling stock entering the neighbouring network. Although the subsequent process of retrofitting rolling stock is slower, the overall shortening and delay in migration for operators making heavy investments – particularly in the early years – will lead to increased costs and further operational risks. The outcome for the IM is more or less the same as in the baseline scenario; here too, the delay in migration will lead to higher costs as a result of factored-in inflation.

- **Scenario G** again models, in contrast to Scenario E, the impacts of a situation where the neighbouring network's IM opts for **the opposite approach** for later migration – **migration with dual terminals**. This situation is illustrated in Figure 6. Operators of their own networks must therefore install dual terminals (2) in advance on vehicles that will temporarily enter another network, leading to increased investment at the start of the migration phase. Terminals supporting only FRMCS (4) may be installed on vehicles operating solely on the operator's own network, and only once the operator's own FRMCS infrastructure is fully operational. Operators on the foreign network, on the other hand, may use GSM-R, which remains in operation even after full migration to FRMCS (4). Whilst there are no cost implications for the domestic infrastructure manager, accelerated investment by operators at the start of the migration phase may lead to higher overall costs and further operational risks. Equipping different vehicles with different types of terminals is also likely to affect operators' OPEX (modelled here as a 50 per cent increase in maintenance costs due to a lack of more precise data).

Figure 6 – Scenario with a different type of migration in the second network



The analysis shows that significant differences in the timing and method of migration between neighbouring countries are undesirable. **The procedure and timeline** for **migration** among transport operators are dictated by the IM of the network that will undertake the migration second (last). Differences in timing result in **a shorter migration period for transport operators,** but with costs accumulating at the start of the process. For a smaller network carrying out migration at a later stage, there is **a risk that the IM of the larger neighbouring network will be unwilling to coordinate** the phasing-out of GSM-R, thereby significantly restricting the interoperability of vehicles on its network. An IM opting for an early transition to a dual infrastructure without coordination with neighbouring networks exposes its operators to the risk that they will have to **install dual terminals** to ensure interoperability with the neighbouring network, and the increased costs on both sides will be partially negated.

4 Legislative and organisational conditions

Chapter 3.3 discussed the obstacles and disincentives anticipated during the future implementation of FRMCS, some of which are rooted in the existing legal framework. This framework comprises

- Technical Specifications for Interoperability (TSIs), in this specific case the CCS TSI as set out in Commission Regulation (EU) 2023/1695,
- the rules governing the authorisation procedure for railway vehicles and their types, as set out in Commission Regulation (EU) 2018/545, as amended, and
- the conditions of public support programmes, such as the Specific Conditions of the public support programme 'Ensuring Interoperability in Rail Transport for the period 2023–2028'.

In relation to these and related regulations, the Czech Republic's representatives at international level within the European Commission's bodies and the standardisation institutions shaping European railway legislation should advocate for

- a more flexible **legislative** framework **that does not directly impose** controversial **substantive obligations** (an example of such an initiative is the ERJU's plan to amend the TSI Statute, whereby the extensive mandatory technical annexes are to be replaced by harmonised technical standards to which the TSI Regulation will merely refer);
- technical standards **that minimise the interdependence and functional interconnection of ERTMS system components** (an example is the proposal by DB and SNCF [1] to separate the specification from the hardware and software for the FRMCS, allowing vehicles to be fitted with compatible hardware in advance and the final FRMCS specification to be implemented solely through software upgrades); and
- when incorporating technical innovations into individual components, ensure maximum backward compatibility, which further limits the impact of changes to one component on related components (examples include more acceptable alternatives to the TSI CCS 2023 with a significantly reduced scope of required recertification – a solution using an additional functional block to the existing ETCS BL 3 (**the** so-called FRMCS **adapter**) or **the** so-called **'light' version**, which implements the Coordinating Function and the FRMCS Communication Function in accordance with the TSI CCS 2023 specification, but does not alter the safety functions, whilst the ETCS application itself remains BL 3 (SV 2.1);
- to push for **the relaxation of railway vehicle approval procedures,** so that, in justified cases, the subject of approval is not the vehicle as a whole but only individual components (an example of this is, once again, the separately specified hardware components as proposed by DB and SNCF [1]), so that the approval of a component within a vehicle – and, in particular, the assessments drawn up by notified or designated bodies – is transferable to its integration into vehicles of similar design and intended use;

at national level, **the relaxation of conditions for financial support** in the railway sector so that

- not only the installation of the listed components but also their modernisation, including software updates, is accepted as eligible expenditure under such programmes, provided this is necessitated by changes to technical regulations, where applicable, to ensure a legal entitlement to such subsequent support if it was granted for the component in question at the time of its installation (such an amendment would address the failure of public support where ongoing changes to requirements and regulations are not sufficiently reflected in the commercial availability of products, and the project fails to meet its ultimate objective within the given timeframe);
- the conditions regarding the project's sustainability period and the associated restrictions on transfers of ownership were relaxed, in particular so that this period could end in the event of a significant change to the technical regulations with which the project is required to comply.

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