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

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CZECH RECOVERY PLAN

History of changes

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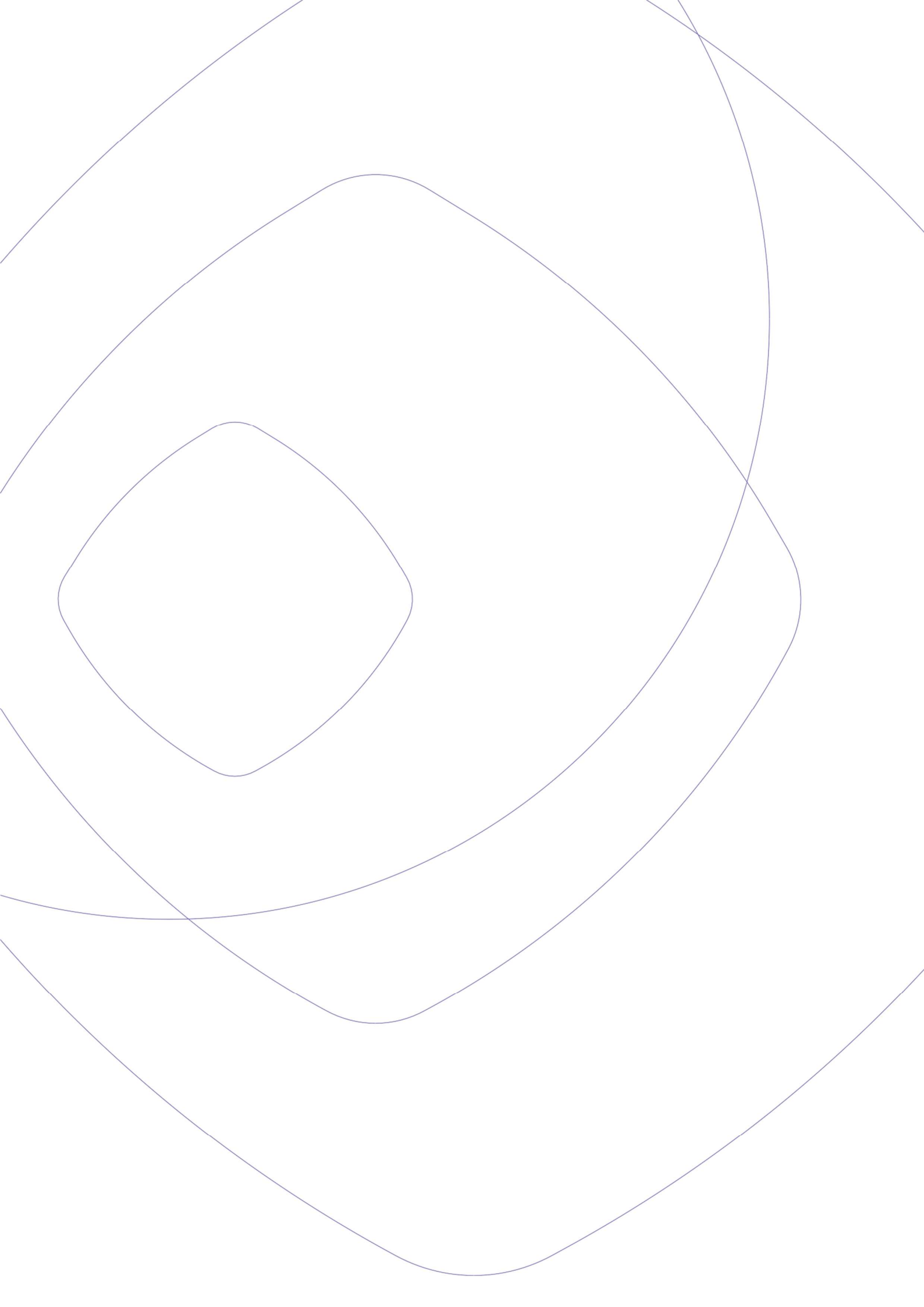


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Management summary

This study addresses the specific conditions for implementing the Future Railway Mobile Communication System (FRMCS) in the Czech Republic, particularly in the primary network infrastructure managed by Správa železnic s.o., taking into account the existing strategic plans for development of railway transport in the Czech Republic, as well as the technical and economic constraints of the legacy GSM-R system. In addition to published and online sources (cited in chapter 6), the study incorporates the **opinions of members of a working group composed of the author and representatives of the freight and passenger carriers associations ŽESNAD and SVOD Bohemia, Správa železnic s.o., the Ministry of Transport, the Ministry of Industry and Trade and delegates of the Czech Republic to Europe's Rail Joint Undertaking (ERJU) and Union des Industries Ferroviaires Européennes (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 the FRMCS standardization, was taken as representative of the applications needed to support existing and future railway operations. The user requirements also classify these applications in terms of criticality. For the purpose of the study, an **own translation of the relevant parts of the FRMCS URS** was prepared, taking into account the established Czech railway terminology and the factual specifics of the Czech railway operation, as presented by representatives of the Ministry of Transport and the SVOD/ŽESNAD associations. That translation and an updated dictionary of relevant terms and definitions is appended to the Czech version of the present study. The attachment will be submitted to the EC Translation Service in Luxembourg, where **it will be used to refine the translation of the EC regulations on railways into the national language version**. The details of this output are summarized in chapter 1.2 of the present study. Based on the list of applications, a questionnaire was drawn up, mapping the perspective and importance for the Czech railway industry. The methodology used in the questionnaire is taken from an older study prepared for ERA in 2016, so its outputs allow us to compare the views of Czech railway representatives with the European context. Chapter 1.1 of the present study is dedicated to evaluating the importance of individual applications, based on the questionnaire.

Chapter 3 is devoted to the possible target coverage of the railway network by the FRMCS system. In each subsection, dedicated to individual RMR bands, MNO bands (Chapter 2.3) and other variants of radio access (Chapter 2.4), the technical conditions of use, basic characteristics of signal propagation and relationships with other bands with regard to possible mutual interference are summarized. Specifically for the 900MHz band (chapter 2.1), coexistence with GSM-R is discussed (chapter 2.1.3). Chapter 2.2 (dedicated to the 1900MHz band), discusses the specifics of TDD band use, the limitations and potential benefits. The main conclusion of the analysis is that **densification of the network of base stations (gNB)** is necessary to deploy the FRMCS system in the **1900MHz** band, even though 100% coverage is not feasible. Over the longer term, possible use of this band should not be excluded from the FRMCS planning perspective.

The communication requirements (specifically the throughput of the radio access network) were taken from the UIC and ERA working papers and technical reports and compared with the results of the NR RAN simulations presented in ETSI technical report TR 103 554-2 [3]. The results of this comparison, presented in chapter 2.6 of the present study, show that to provide communication support for the entire set of critical applications, any one RMR band, by itself, does not have enough capacity. It will be necessary to build the FRMCS system gradually, as an overlap of both bands, or by shifting some part of the communication traffic to bands operated by an MNO. That target state should be considered when optimizing the costs and logistics of the initial migration steps.

The next part of the present study is devoted to the **evaluation of migration scenarios**. The evaluation proceeds from theoretical scenarios taken from an earlier study prepared for ERA in 2016, to sub-variants reflecting the specifics of the current situation in the Czech Republic. The individual scenarios cover the order of migration of infrastructure and vehicle equipment. In chapter 3.4, the transition to bands outside of 900 MHz and the effect of incompatibilities within FRMCS or in connection with the European Train Control System (ETCS) are evaluated for a single network. Chapter 3.5 considers the order of migration in relation to cross-border traffic with a larger neighbouring railway network. The evaluation of the scenarios also includes comparing their costs using a model taken from a previous study prepared for ERA and adapted to the current conditions in the Czech railway network in the 2020s. The main conclusion of the comparison is that **the scenario with dual FRMCS/GSM-R terminals** installed on vehicles is more investment-friendly for carriers and more resistant to external influences, such as material differences and migration time shifts in neighbouring railway networks. However, it is blocked by **the lack of time** for pilot-testing 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 ch.4.3 and a comparison of these results with a survey of Western European railway administrations and carriers carried out for ERA in an earlier study.

The evaluation of the options and the content of the discussion in the working group for this study led to **proposals for changes in the legislative framework**, mainly concerning **stabilisation of the technical regulatory environment, vehicle certification and the conditions of 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 operation of ETCS, which had significant impacts on the profitability of migration on the side of railway undertakings and are one of the reasons for the minimal motivation of the Czech railway sector to switch to FRMCS.

Abbreviations used

3GPP	*3G Project Parnership* - a consortium created to develop new generations of standards for mobile communication
4G LTE	*Fourth Generation Long Term Evolution* - a term for the 4th generation of 3GPP's mobile communication technologies
5G NR	*Fifth Generation New Radio* - designation for 5th generation of 3GPP's radio access technology
5GC	*Fifth Generation Core* - collective name for the technical means forming the core of the 5th generation mobile communications network
5GS	*Fifth Generation System* - collective name for the network and technical means of 3GPP's 5th generation of mobile communication
5QI	*5G Quality Indicator* - an element of the mobile access control protocol that indicates the desired transmission quality class
ACLR	*Adjacent Channel Leakage Ratio* - parasitic radiation of power into an adjacent channel
AP	*Access Point* - an access point of a communication service, specifically a WLAN element communicating with end terminals
ATO	*Automatic Train Operation* - general term for a technical system for automatic train operation
ATP	*Automatic Train Protection* - general term for automatic protection applications for trains
BL	*Baseline* - designation for a stable core of performance functions and other characteristics of ERTMS subsystems
BS	*Base Station* - for a mobile communication system
CAPEX	*Capital Expenditure* - investment costs
CBA	*Cost/Benefit Analysis* - project evaluation methodology
CCTV	*Closed Circuit Television* - a video system for a specific private use; usually for security surveillance
CEPT	*European Conference of Postal and Telecommunications Administrations* - a European association of postal and telecommunications *administrations* providing commercial, operational and legislative cooperation and technical standardisation
CU	*Control Unit* - 5G NR architecture block, implementing remote logic layer and gNB control for locally or remotely operating DUs
DCS	*Dynamic Channel Selection* - frequency selection mechanism for DECT systems
DL	*downlink* – data transfer from the network to the mobile terminal
DMR	*Digital Mobile Radio* - a narrowband digital radio communication system based on the ETSI standard TS 102 361 series
DU	*Distributed Unit* - a 5G NR architecture block remotely implementing the physical transmission layer for gNB
ECC	*Electronic Communications Committee* – a high-level committee under CEPT providing policy guidance and rule making for electronic communications in the European area
EDOR	*ETCS Data Only Radio* - GSM-R data modem used for ETCS communication (generally ATP)
EIRP	*Equivalent Isotropically Radiated Power* - radiated power of a radio interface spread in all directions
EC	European Commission
eMBB	*Enhanced Mobile BroadBand* - designation for 4G/5G network services optimized for high bandwidth
EP	European Parliament
ERA	*European Railway Agency* - established by the EU for the development and unification of European railways, it performs, among other things, the function of a pan-European body for the approval of railway components
ERC	*European Research Council* - research funding organisation

ERJU	*Europe´s Rail Joint Undertaking* - a joint venture between the EU and private companies to support research and development of innovative solutions for European rail; successor to the Shift2Rail Joint Undertaking
ERTMS	*European Rail Traffic Management System* - a complex of systems for train control and signalling, critical voice communication and radio communication
ETCS	*European Train Control System* – an integrated rail traffic management system defined by European standards, including critical voice and data services for train protection and control
ETSI	*European Telecommunications Standards Institute* - a non-profit organisation for the development and management of telecommunications and radio standards
EUSPA	*EU Space Programme Agency* - EU agency for the development, operation and support of satellite technology applications
FDD	*Frequency Division Duplex* – a technique that enables bi-directional radio communication by pairing uni-directional channels
FR	France (international abbreviation according to ISO3166-1)
FR1/FR2	*Frequency Range 1 / 2* - frequency ranges used for railway communications, with fundamentally different physical characteristics
FRMCS	*Future Railway Mobile Communication System* - successor system to GSM-R in ERTMS, based on 5th generation 3GPP mobile networks
FUP	*Fair User Policy - a* mechanism for allocating limited network capacity among users, typically by limiting their speed after a quota of data volume has been exhausted
GEO	*Geostationary Earth Orbit* – an orbit that requires satellites to move at the speed of the Earth's rotation so the satellite seems to be stationed over a location on the Earth's surface
gNB	*Generalized Node B* - a node in the 5G RAN that provides connectivity between the mobile terminal and the core of the base station network
GNSS	*Global Navigation Satellite System* - a general term for satellite navigation systems without regard to the provider or the system's detailed parameters
GoA	*Grade of Automation* - the degree of automation in an automatic train control system
GPS	*Global Positioning System* - a satellite navigation system operated by the US Department of Defense
GS	*Ground Station* - terrestrial component of a satellite system
GSM-P	*GSM Primary* - a term used to denote the primary bands for GSM: 890 - 915 MHz paired with 935 - 960 MHz
GSM-R	*Global System for Mobile radio - Railway* - a mobile communication system adapted to the requirements of railway transport
HAPS	*High-Altitude Platform Station* - part of a communication system located on an aerial vehicle (a dirigible, tethered balloon or drone)
HARQ	*Hybrid Automatic Repeat Query* - a mechanism for correcting block transmission errors, using simultaneously requested block repeats with self-correcting (forward) codes
HD	*High Definition* - a family of standards for TV images (e.g. 1920 x 1024 pixels)
HHT	*Hand-Held Terminal*
HV	*Hnací Vozidlo* - a driving vehicle
HW	*Hardware* - electrotechnical support for a communication system
ID	Identifier
IM	Infrastructure Manager - general description of the role of an entity in the railway sector
IMS	*IP Multimedia Subsystem* - an application layer on top of the mobile transport layer providing uniform multimedia services (standardized by 3GPP)
I/O	*Input/Output*

IoT	*Internet of Things* - a term for the communication of automated machines over a mobile network (their data traffic differs from human users)
ISD	*Inter-Site Distance* - the distance separating transceivers in adjacent cells of a radio communication system
ISL	*Inter-Satellite Link* - a wireless link supporting line-of-sight communication between satellites
ITU-R	*International Telecommunication Union - Radiocommunication sector* – the section of an international standards and coordination body responsible for radiocommunication
JESNAD	Association of Railway Freight Carriers of the Czech Republic, z.s.
LAN	*Local Area Network* - designation for a network providing data services on a local scale specifically with both control and data planes according to Ethernet standards
LEO	*Low Earth Orbit* - a system of satellites orbiting in low earth orbit
LoS	*Line of Sight* - line-of-sight radio communication
MAC	*Medium Access Control* - the process of accessing a shared physical medium of communication, here specifically in the radio interface of mobile networks
MCX	*MIssion Critical Anything* - collective name for critical services provided by the network based on 3GPP standards
MD	Ministry of Transport of the Czech Republic
MEO	*Medium Earth Orbit* - a system of satellites orbiting at medium altitude
MIMO	*Multiple-Input Multiple-Output* - designation of technologies for transmitting and receiving multiple streams of radio data in parallel
mMT	*Massive Machine Type communication* - designation for 4G/5G network services optimized for a large number of devices
MNO	*Mobile Network Operator* - here specifically a cellular network providing public communication services
MOCN	*Multiple Operator Core Network* - a shared mobile network architecture with a common set of core functions
MIT	Ministry of Industry and Trade of the Czech Republic
MT	*Mobile Terminal* - subscriber equipment for mobile network access; in English language texts, the abbreviation is UE (User Equipment)
NB-IoT	*Narrow Band Internet of Things*
NLoS	*Non-Line of Sight* - radio communication on a path with indirect visibility (reflected beam)
NPV	*Net Present Value* - an aggregate measure of economic value over a longer period, used in the study to denote liabilities without a negative sign
NTN	*Non-Terrestrial Networks* - collective designation for networks whose BS/APs are not on the earth's surface
OFDM	*Orthogonal Frequency Division Multiplexing* - a method of modulating digital signals to a group of narrowband subcarriers
OPEX	*Operational Expenditure*
P25	A narrowband digital radio communication system based on the APCO-25 standard
PDCP	*Packet Data Convergence Protocol* - control protocol for data flows through the radio interface of a mobile network
PLMN	*Public Land Mobile Network* - the land portion of a mobile communications network providing a public service
PPDR	*Public Protection and Disaster Relief* - collective designation for emergency response teams
QAM	*Quadrature Amplitude Modulation* - designation for modulation with a larger number of phase-amplitude states
QoS	*Quality of Service - a* set of indicators to measure quality of service
QPSK	*Quadrature Phase Shift Keying* - a type of modulation of a digital signal to an analogue carrier with 4 states
RAN	*Radio Access Network*

RFID	*Radio Frequency IDentification* - special communication for radio frequency identification with minimal resources
RINF	*Registers of Infrastructure* – maintained by ERA, the European Union Agency for Railways
RLC	*Radio Link Control* – physical layer control of the mobile network radio link to the mobile terminal
RMR	*Railway Mobile Radio* - a common designation for frequency bands reserved by the ECC Recommendation for railway use in Europe
RRB	*Radio Resource Block* - a logical unit for the organisation of signals on the radio interface of a mobile network
RRH	*Remote Radio Head* - a block of mobile network architecture implementing a remote physical layer of transmission for the BS
RSRP	*Reference Signal Received Power* - a key measure of signal level for LTE networks
RSRQ	*Reference Signal Received Quality* - a key measure of signal quality for LTE networks
SIM	*Subscriber Identity Module* - electronic means of storing in a secure manner the identification data of a mobile network subscriber
SINR	*Signal to Interference and Noise Ratio*
SLA	*Service-Level Agreement* - a contract between a service provider and its customers which documents what services the provider will furnish and defines the service standards the provider is obligated to meet.
SNR	*Signal to Noise Ratio*
SPOŽES	Compendium for valuation of railway structures – valuation methodology at the feasibility study stage developed by SFDI
SRCC	*Smart Rail Connectivity Campus* - a research, development and testing centre for innovation for the rail sector, located in Saxony (Germany)
SRS	*System Requirement Specifications* - UIC document describing the uses of FRMCS functions (part of the CCS TSI Annexes)
SS-RSRP	*Secondary Synchronization Reference Signal Receive Power* - an indicator of the received signal strength before demodulation and decoding, measured on the synchronization component of the radio signal in 4G/5G networks
SVOD	Association of Passenger Railway Carriers z.s.
SW	*Software* – programmed code resources of the infocommunication system
TC RT	*Technical Committee Rail Telecommunications* - ETSI committee responsible for rail telecommunications
TCMS	*Train Control and Management System* - a system for controlling and managing auxiliary technologies on board a train (in the case of traction, only in ways that do not affect its running)
TDD	*Time Division Duplex* - a temporal method of dividing the direction of transmission in the same channel
TETRA	A narrowband digital radio communication system for emergency services, based on the ETSI standard EN 300 392 series
TOBA	Telecom/Third-Party Operator Band Access
TSI CCS	*Technical Specifications for Interoperability relating to the Control-Command and Signalling subsystems of the rail system in the European Union* - general designation for the EC Regulation setting rules for the interoperability of the control-command and signalling subsystems of European railways
UAS	*Unmanned Aircraft System* - pilotless air vehicle (a drone)
UIC	*Union Internationale des Chemins de fer,* International Union of Railways - an organisation bringing together states to coordinate the development and operation of rail transport
UL	*Uplink* – data traffic sent from a mobile terminal to the network
UMTS	*Universal Mobile Telecommunications System* - a generic term for 3rd generation 3GPP mobile network technology
UNIFE	*Union des Industries Ferroviaires Européennes* - an interest group representing the European rail industry

URS	*User Requirements Specification* - UIC document [35] describing the use of FRMCS communications from a user's perspective
VLEO	*Very Low Earth Orbit* - a system of satellites travelling in a very low (near Earth) orbit
VRT	*Vysokorychlostní trať* - high-speed railway (project in the Czech Republic)
WG	*Work Group*
WiFi	Collective name of a series of backwards-compatible WLAN standards
WLAN	*Wireless Local Area Network* – a radio-based LAN

1 Applications to support railway operations

1.1 FRMCS applications used in the Czech Republic

The publicly discussed strategic plans for development of railway transport in the Czech Republic do not currently contain a specific strategy regarding deployment of the Future Railway Mobile Communication System (FRMCS, the successor of GSM-R as a communication component of ERTMS). Nor do the plans link FRMCS to applications in the current version of Strategic Document *ERTMS National Implementation Plan* [26]. The ERTMS plan's FRMCS chapter only states that the deployment cannot be responsibly planned because its technical specifications are not finalised and there are no corresponding products available on the market. The ERTMS plan also does not deal with applications for railway operation support, with the exception of the application for train protection, ETCS. Moreover, the term „application" in the FRMCS standards is used differently from the usual ICT practice. Here it is meant in the sense of a "communication task serving applications". The applications themselves are grouped by this mechanism according to purpose, with the assumption that their individual implementations will in principle have similar communication requirements.

Consensus acceptance of a set of applications, and the subset to support during the migration phase of the transition from GSM-R to FRMCS, has changed during development of FRMCS standards. Table 1 captures the different views on the importance of critical communication applications, each column showing the source of the assessment. Terms used in Table 1 are explained in this list:

- „**UIC URS application"** is a reference to the application definition in Annex 1 of this study
- The term **„support in GSM-R"** represents the basic set of applications supported in the current EIRENE ERTMS (GSM-R plus ETCS, now ATO to GoA2). Support for all these applications is a prerequisite for migration. ATO support is linked to the GSM-R packet service (PS), which is not yet operational in some countries.
- **„Report 74"** represents the 2020 view and indicates the phase in which [5] included the required capacity in the FRMCS requirements. (**Migr** is the migration phase, during which there must be parallel support for FRMCS and GSM-R. **Target** is the target state after GSM-R is decommissioned.) To the subset already identified for support during migration, it added the operationally promising applications of Emergency Call to Public Network, Remote HV Control, Critical Video and support for Train Location applications (particularly necessary for the operation of voice applications). The ensemble also included On-board Intelligence and Sensors, a group of applications that broke down into smaller units as development progressed and virtually disappeared from the UIC definitions.
- **„FRMCS planning"** represents application support plans within the FRMCS V2 and V3 standards, according to selected planning documents (specifically [27] and the latest plan so far, which is part of chapter 9.2 of draft version [28] V1.1). Those were developed after release of the FRMCS V1 specification, CCS 2023 TSI, and were intended to be validated by trial deployments. V2 represents the applications forming the basis of interoperability. These are intended for operational testing in the MORANE 2 programme. Together with the applications included in V3, they form the set intended for the CCS 2027 TSI specification (FRMCS Baseline 1), which will be complete enough to allow the production, purchase and installation of FRMCS components on vehicles and infrastructure. The availability of FRMCS components is a prerequisite for migration. Approximately one third of the applications do not yet even have functional requirements defined within FRMCS and will only be subject to standardisation in V4 and above. Their introduction later could require additional upgrades to the FRMCS equipment installed during migration.
- **„The survey in the Czech Republic"** represents the opinions collected in a survey submitted to the participants of the working group preparing this study: two freight carriers of different sizes, a smaller passenger carrier and SŽ as a representative of the infrastructure manager. The interest in applications is assessed similarly to the motivation of the respondents - on a scale from 0 (irrelevant) to 5 (critical to operations). For carriers, the average rating is given, with values in parentheses that are not predictive due to the large variance of the ratings. The differences are then commented on in detail in the following text.

Table 1 - Communication for critical applications in the UIC URS structure

Applications according to UIC URS		Support in GSM-R	Report 74	FRMCS planning	Survey	
					carriers	IM
5.1	Outgoing voice communication from the driver on the train towards the train dispatcher	Yes	Migr	V2-V3	5,0	5
5.2	Incoming voice communication in the train from the train dispatcher towards the driver	Yes	Migr	V2-V3	5,0	5
5.3	Voice communication between drivers of different trains or ground users	Yes	Migr	V2-V3	5,0	5
5.4	Voice communication during harnessing	Yes	Migr	V2-V3	5,0	5
5.5	Line maintenance voice communication				(2,3)	4
5.6	Voice communication for scrolling	Yes	Target	(V2) V3	5,0	5
5.7	Public emergency call		Migr	undefined	5,0	4
5.8	Ground staff voice communication			--	3,7	5
5.9	Automatic Train Protection (ATP), ETCS Communication	Yes	Migr	V2	5,0	5
5.10	Automatic Train Operation (ATO) communication	PS	Migr/Target	V2-V3	4,3	5
5.11	Data communication for lockout management			undefined	(2,3)	3
5.12	Communication for the track maintenance warning system			undefined	(3,3)	5
5.13	Locomotive remote control communication		Migr	undefined V2-V3	5,0	2
5.14	Monitoring and management of critical infrastructure			--	(2,7)	4
5.15	Railway emergency communication	Yes	Migr	V2	5,0	5
5.16	Communication between on-board safety equipment and the ground system		Target	V3	5,0	0
5.17	Public emergency communication with train			undefined	3,0	1
5.18	Lone worker			undefined	(2,7)	4
5.19	Voice recording and access to recorded data			--	5,0	5
5.20	Data recording and access to records			--	5,0	4
5.21	Data communication for shifting			--	4,0	0
5.22	Train integrity monitoring data communication		Target	V3	4,3	0
5.23	Public emergency warning		Migr	V2-V3	4,3	4
5.24	Outgoing voice communication of train crew towards the ground user			undefined	(2,7)	0
5.25	Incoming voice communication from the ground user towards the train crew			undefined	(2,7)	0

Applications according to UIC URS		Support in GSM-R	Report 74	FRMCS planning	Survey	
					carriers	IM
5.26	Emergency communication for railway staff			undefined	5,0	5
5.27	Critical live video		Migr	V2-V3	(3,7)	0
5.28	Early warning system - safety related		Target	V2-V3	4,7	5
5.29	Data communication of virtual clamping		Target	V3	3,3	0
5.30	Securing parked trains			undefined	4,7	0

For the applications already in operation - voice, emergency communications and train protection, data logging and access (5.27) - there is agreement among all sector participants on the high importance of such applications. In other cases, for various reasons, the ratings differ, but each application is of at least moderate importance to some participants:

- Seven applications with high ratings are only **relevant to carriers**, while infrastructure managers (IM) marked them as irrelevant (0).
- For five applications - **Critical Infrastructure Monitoring and Control** (5.14), **Ground Personnel Voice Communications** (5.8), **Lone Worker** (5.18), **Line Maintenance Voice Communications** (5.5) and **Line Maintenance Alert System Communications** (5.12) - the situation is reversed: they are of little relevance to operators but highly rated by IMs. In addition, for the last three, related to track maintenance, there is a large variance in the operators‘ views. On the one hand, they generally recognise its importance for the safety of staff. On the other hand, they are concerned about making the driver responsible for safety and indicate that such communication is not a matter for the carrier.
- There are also large differences in the carriers' views on **Data Communication for the management of lockout operations** (5.11) and **Voice Communication between train crew and ground users** (5.24 and 5.25). The use of such communication by carriers is sparse (e.g. only for work trains) or non-existent (freight transport without train crew). Yet in general, as in the previous case, its usefulness for other rail services is recognised (rating 3-4). IM expresses interest only in the former.
- There is a similar view of **Critical Video** (5.27), which is the largest expected consumer of transmission capacity anyway, unavailable in frequency bands below 2GHz (see Chapter 2.6). The lukewarm opinion about video’s utility in general is complemented by the unjustifiability of the costs of the communication and IT infrastructure for carriers. IM sees no use.

Like the previous one, Table 2 summarizes the view of the importance of non-critical applications, classified as performance by FRMCS standards. These applications are intended for service use and the aim is to improve the efficiency of rail operations.

Applications are also usually classified as **non-interoperable** in the FRMCS standards, given that they are used by the vehicle operator (or owner or manufacturer) for internal purposes so they are not meant to be accessible to other entities. Therefore, they **do** not need to be interoperable in a technical sense. The communication scheme of such applications is different from that of interoperable applications. The vehicle connects all FRMCS domains to the home domain (i.e. the country of registration or residence of the using entity).

None of these applications are supported in GSM-R. They are operated by MNO networks under commercial conditions. The meaning of the other columns in Table 2 is the same as in Table 1. Most of the applications do not yet have even functional requirements defined within FRMCS. They will be subject to standardisation only in V4 and higher.

Table 2 - Communication for performance applications in the UIC URS structure

Applications according to UIC URS		Report 74	FRMCS planning	Survey	
				carriers	IM
6.3	Voice communication between drivers of multiple trains outside ground users	--	undefined	5,0	0
6.4	Voice communication on the train	--	undefined	4,0	0
6.5	Line telephony	--	undefined	3,0	5
6.6	Voice communication in the train towards passengers	--	--	(3,3)	0
6.7	Station announcements	--	undefined	2,3	2
6.8	Communication in stations and service facilities	--	undefined	4,3	4
6.9	Train telemetry communication	Target	V2-V3	5,0	5

Applications according to UIC URS		Report 74	FRMCS planning	Survey	
				carriers	IM
6.10	Infrastructure telemetry communications	--	undefined	(3,3)	5
6.11	Remote control of on-board equipment	Target	undefined V2-V3	5,0	0
6.12	Monitoring and management of non-critical infrastructure	--	undefined	(2,7)	4
6.13	Non-critical live video	--	undefined	3,8	2
6.14	Wireless data communication for train staff	--	undefined	4,0	0
6.15	Wireless data communication for railway staff on platforms	--	undefined	(2,7)	5
6.17	Help to the driver - train performance	--	undefined	4,3	2
6.18	Data communication for train departure	--	undefined	5,0	0
6.19	Messaging services	--	--	5,0	5
6.20	Data transfer	--	--	5,0	5
6.21	Recording and broadcasting information	--	undefined	5,0	5
6.22	CCTV archive transfer	--	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 ratings in Table 2 are similar to those for critical applications:

- Eight applications are only **relevant to carriers**, but not all are of key importance to carriers. Voice communication in the train towards passengers (train radio) (6.6) is only relevant for passenger carriers, but some freight carriers also identified it as (generally) useful.
- **The transfer of CCTV archives** (6.22) is assessed similarly, but some freight forwarders consider the resulting data volumes too large for systematic central archiving (see example below), and the needed IT resources not cost-justified. They prefer selective off-line transfers. There is a similarly mixed assessment of **Augmented Reality Information Transfer (**6.24), which some respondents cannot incorporate into their procedures.
- Four applications - **In-track telephony** (6.5), **Infrastructure telemetry communications** (6.10), **Monitoring and control of non-critical infrastructure** (6.12) and **Wireless data communication for railway staff on platforms** (6.15) are again of little relevance to operators but highly rated by IM. The variance between the views of the hauliers is again due to the difference between generally acknowledged relevance but de facto irrelevance for freight operators.
- Sectoral interest in **live video** (applications 6.13 and 6.23), which is the largest expected consumer of bandwidth, requiring transmissions in the 5G frequency bands above 2GHz, with major impact on the terrestrial infrastructure needed to support such communication, is systematically low, and the lowest for IM.
- On the other hand, the interest in **Real Time Speech Translation** (application 6.25) is surprisingly high among all, because it addresses real problems in the ever-expanding cross-border transport of freight and passengers. The proposed alternative measure is the (probably very unpopular) proposal to introduce a single pan-European transport language.

There is a consensus on the high and general importance amongst both carriers and IMs for the applications that are already widely used: i.e., **Train Telemetry** (6.9), **Messaging Services** (6.19), **Data Transfer** (6.20) and **Recording and Transmission of Information** (6.21). The first of these includes the measurement of electrical HV consumption, required by the TSI, which is one of the few non-critical applications that is also operated on GSM-R.

All **video usage** is currently considered an extremely demanding application. An example is a system for recording the situation around a moving vehicle. This was discussed with a trucking company during the survey. In this case, the recording is continuously taken from up to 4 HD cameras on the vehicle and converted into a continuous 4MB/s stream - significantly more than the capacities expected to be available in FRMCS in the RMR bands (see Chapter 2.6). Therefore, for real-time situational previews, only 1s samples of footage will be transmitted. A complete local recording represents 20 - 40GB per day on each vehicle, 2 - 4TB of data per day for the entire HV fleet. However, the actual requirement for incident handling is a fraction of this volume: fifty 5-minute recordings of 15GB, i.e. 0.4 - 0.7%. Transferring a single record in a still-acceptable 20 minutes requires speeds of 2Mb/s and above from any point on the line.

The UIC classification of applications currently includes 4 **business applications**, representing wireless access for staff and passengers in different areas of the railway. These applications are not subjects of the present study.

1.2 Proposals for changes to standards

In discussions about the FRMCS URS definitions of application groups, it became apparent that there is no generally accepted Czech equivalent in the industry. There are several reasons for this:

- The FRMCS URS document itself did not become an annex to the issued CCS 2023 TSIs (EC Regulation 2023/1695), so there was no official translation. In addition, for other documents that have been translated within the TSIs (and other pan-European railway regulations), the translations provided by the EC and EP bodies as part of the legislative process appear not to respect the established Czech railway terminology.
- Officially available lexicons of transport terminology, including railway terminology, do not reflect the current state of development of the sector, as they have not been updated in the last 10 years. The national Dictionary of Transport Terminology [33] was published in 2010. The UIC RailLexic [34] has the last available update to version 4.0 from 2011.
- The brief definitions of applications in FRMCS URS deviate significantly from railway practice in the Czech Republic, and probably also from the practice of other countries, because they do not distinguish some essential operational meanings and categories terminologically. Examples of this are:
  - the common term "train", which is used for both train and rolling stock;
  - the term "driver" without attributes (the definitions do not distinguish between the driver leading the HV train and the operator of other HVs included in the train);
  - the narrowing of the term "banking" to only unhitched siding (which is less used operationally); and
  - the term "controller", which does not distinguish the individual operational roles of dispatchers..

Therefore, for discussions within the working group of the study, a Czech translation and an associated English-Czech explanatory glossary of the terms used were prepared in agreement with the representatives of the Ministry of Transport and the participating associations of carriers, which the working group proposes to share with the EC Translation Service in Luxembourg as a standard for translations of railway legislation into Czech, e.g. by the Ministry of Transport Department 130 and the transport attaché at the Permanent EC Representation of the Czech Republic. The translation of the FRMCS URS definitions and the glossary are contained in Annex 1 of the Czech version of this study.

2 FRMCS coverage

According to [8], FRMCS (5G NR) **signal coverage** is more complex than GSM-R. Thus, it cannot be expressed in terms of a signal strength threshold, since the transmission quality is affected by many factors such as dynamically chosen modulation, different MIMO schemes, the TDD multiplexing ratio (for the 1900MHz band), link adaptation mechanisms, and function blocks that are not fully standardized, such as the scheduler, among others. The signal quality at a particular location is therefore determined by multiple parameters - RSRP, RSRQ and SINR - quantified additionally from several reference signals. Since adjacent cells can transmit at the same frequencies (radio resource block = RRB), in many cases interference to a cell's signal by signals (gNB and MT) from neighbouring cells is a limiting factor. The final indicator from the user's point of view is the achievable transmission rate, which will vary in the upload direction (to the network) and in the download direction (to the mobile terminal). The signal-to-noise-interference-interference ratio (SINR) is a critical signal parameter for determining this.

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

- the communication speed achievable;
- the possible need for gNB densification (reduction of cell diameters) compared to the existing GSM-R infrastructure in the 900MHz (n100) band; this is influenced by frequency-dependent propagation specificities such as the directional sensitivity of antennas, multipath propagation modes and induced interference;
- interactions with other neighbouring use zones and means to limit them.

A critical point of interference between communications in all the discussed bands is the interference between antennas located within a relatively small area of the vehicle roof. The RMR bands do not significantly interfere with each other, but this is true if at least the basic isolation conditions given by the placement of the individual antennas on the vehicle roof are ensured. However, ensuring these conditions is not trivial due to the high number of antennas both on the side of the replaced system (a typical GSM-R configuration is one on-board voice MT and two EDORs for ETCS) and the new system (acceptable communication capacities are shown by simulations [3] with MIMO 1x4 and 4x2 configurations, that is to say, a minimum of two antennas on the vehicle). If the attenuation provided by the spatial arrangement is not sufficient, possible measures according to [29] and assuming antenna spacing of only 2m, rely on the inclusion of combining filters between the common FRMCS wideband antennas and the radio modules of the individual bands to achieve the necessary suppression of unwanted signals. At the same time, for large-scale deployment of filters, the concerns are [6] the high cost and the weight of the on-board components. The antennas and their terminals for GSM-R always remain separate.

2.1 900MHz band usage

The RMR band for exclusive use by railway communications, commonly referred to *as "*900MHz" but more precisely designated by CEPT as n100, is a dual band for FDD use comprising 874.4-880.0MHz and 919.4-925.0MHz. This is extended by 2x 1.6MHz from the original GSM-R band (876.0-880.0MHz and 921.0-925.0MHz). The assumed possibility of a 3MHz national extension (i.e. to 873-880MHz and 918-925MHz) is not realisable for the Czech Republic. The extended band is expected to be used according to [5]:

- during migration in parallel for the existing GSM-R system and the successor FRMCS (the possible methods are discussed in paragraph 2.1.3);
- Targeted broadband channels with NG technology up to 5MHz, possibly supplemented by several 200kHz NB-IoT channels, operated under ECC Report 318 conditions, intended e.g. for radio communication of infrastructure elements or track maintenance warning system.

For the use of the n100 band by broadband modulations, the CEPT report [4] sets out these conditions in the form of a spectrum emission mask for both directions of transmission. No further coordination with services in adjacent bands would then be required:

- The EIRP transmit power allowed for base stations (gNB in 5G terminology) is reduced in the new band extension to protect traffic in the 880 - 915MHz band compared to the values in the original GSM-R band (for a wideband transmitter operating with the same power throughout the band, the transmit power is limited to what is specified for the lower edge of the used band). Nationally it is possible to allow higher powers if interference is not caused to other services in the band up to 915MHz, or conversely, the transmit power can be limited to 65dBm in the n100 band regardless of bandwidth and channel position.

- For coordination at network boundaries, Recommendation ECC (08)02 sets specific maximum signal levels of the foreign network at and near the boundary (59 or 41dBuV/m, i.e. below -66dBm).
- The permitted transmit power EIRP for vehicular MT is 23 to 31dBm with an adjacent channel loss (ACLR) of at least 37dB and an emission mask compliant with 3GPP requirements for LTE/NR. For handheld terminals the permitted transmit power is only 23dBm with an ACLR of 30dB. In both cases the MT shall have transmit power control operational and activated.

2.1.1 Signal propagation conditions

According to [7], FRMCS, unlike GSM-R, does not produce the same coverage in both transmission directions. The coverage is essentially determined by the upload conditions, even with increased MT transmitter power (31dBm, i.e. less than 39dBm in GSM-R, moreover with a significantly wider bandwidth). The more complex transmission method is more sensitive to conditions at the edge of the coverage cell, where it is no longer sufficient simply to observe the minimum RF signal level, as is sufficient with GSM-R. Nevertheless, the usable coverage of FRMCS in the 900MHz band is considered similar to GSM-R.

ETSI has performed quite extensive propagation simulations with several different simulation tools, the results of which are summarized in [3]. Each of the three tools used proved to be more suitable for modelling different aspects of the transmission. While two of the models allowed simulation under different MIMO configurations (with quite different results in transmission rate), the third model was able to model the effect of different spectrum allocations with regard to neighbouring cells (reuse factor) and driving speed (Doppler effect).

Modelling shows the following conditions for the 900MHz band:

- MTs with transmit power of 31dBm are practically usable, although upload parameters are significantly affected by the transmit power in both urban environments and in open countryside. For downloads, simulations in both environments showed a significant anomaly in performance near the BS (gNB): due to interference with the signal from the rear lobe antennas on the other side of the same mast and the high directivity of MIMO transmissions. Within 300m from the base station, both SINR and transmission rate drop to values close to the cell edge in the open landscape (at a distance of 1-2km).
- Uplink transmission ratios in urban environments are worse than in the open countryside, even though the cells are planned to be only half the size. The SINR at the receiving gNB antennas drops below 2dB for half of the MTs at the cell edge (below 7dB in open countryside). As expected, this is due to the higher proportion of NLoS propagation as well as the higher attenuation of LoS propagation (lower antennas and higher buildings).
- The modelling showed a clear optimum in the MIMO configurations investigated, ranging from 1x2 to 2x4 (exceptionally 4x4). The 2x4 configurations gave the best results for the uplink parameters (with better interference suppression, directivity and gain from spatial multiplexing and effective receiving antenna area). But so far their use is unrealistic, as standards even in Rel18 allow only 1 transmit antenna per MT. 4x2 configurations are well suited for downlink (installing 4 antennas on a vehicle would improve the ratio longer, but is not realistic for space reasons). Simulations for open countryside, and even urban environments give the same results regarding MIMO.
- Configured (fixed) bandwidth sharing between neighbouring cells (Frequency Reuse), which aims to reduce interference at the cell edge at the cost of reducing the speed in the centre of the cell, did not give clear results and the study recommended leaving the bandwidth organisation to the automatic mechanisms of 5G NR.

A good illustration of the ways in which reception conditions for FRMCS differ from GSM-R is the **result of preliminary planning** for the vicinity of theThionville (FR) railway station, presented in [8], for operating for the 900MHz band with a cell diameter up to 8km in a flat landscape with suburban housing, masts about 23m high and base station antenna gain of 17dBi:

- GSM-R benchmarking showed a level of -95dBm at the edge of such a cell, meeting EIRENE standards.
- The signal level for FRMCS (SS-RSRP) at the same location was -115dBm and SINR around 0dB. In such conditions (at the limit of using QPSK and 16QAM modulation), the theoretically achievable bit rate is, according to [8] and [3], around 2Mb/s, and the radio planning in the specific cited case predicted at least 480kb/s (downlink with MIMO 2x2 diversity and uplink).

2.1.2 Interference with neighbouring bands

For the RMR 900MHz (n100) band, [5] addresses the possibility of mutual interference with the following radio communication bands:

- The reception of base station (uplink) networks in the band up to 915MHz is protected by adjusting the mask of permitted transmission powers according to paragraph 2.1 (by reducing the powers of channels extending below 921MHz). FRMCS vehicle stations (generally MT), on the other hand, shall be sufficiently resilient to the transmitters of networks in this band.

- The vehicle stations (generally MT) of the FRMCS system must be sufficiently resistant also against transmitters of networks in the band above 925MHz, which is already met by GSM-R receivers designed according to ETSI TS 102 933-1. Most of the same requirements will also apply to FRMCS.
- In addition, FRMCS vehicle stations (generally MT) must be sufficiently robust against short-range transmitters (RFID or data transmission, WiFi 802.11ah) operating in the 915.0-919.4MHz band, which will be ensured by meeting the requirements in ECC Report 313, mandatory for FRMCS receivers.
- Similarly, according to ECC Report 313, FRMCS BS (gNB, uplink) receivers must be resistant to short-range (data) transmitters operating in the 874.0-874.4MHz band. Harmonization of the spectrum for this case is represented by EU Regulation 2022/180 and ERC Recommendation 70-03 from 6/2019, currently already implemented in the Czech Republic.

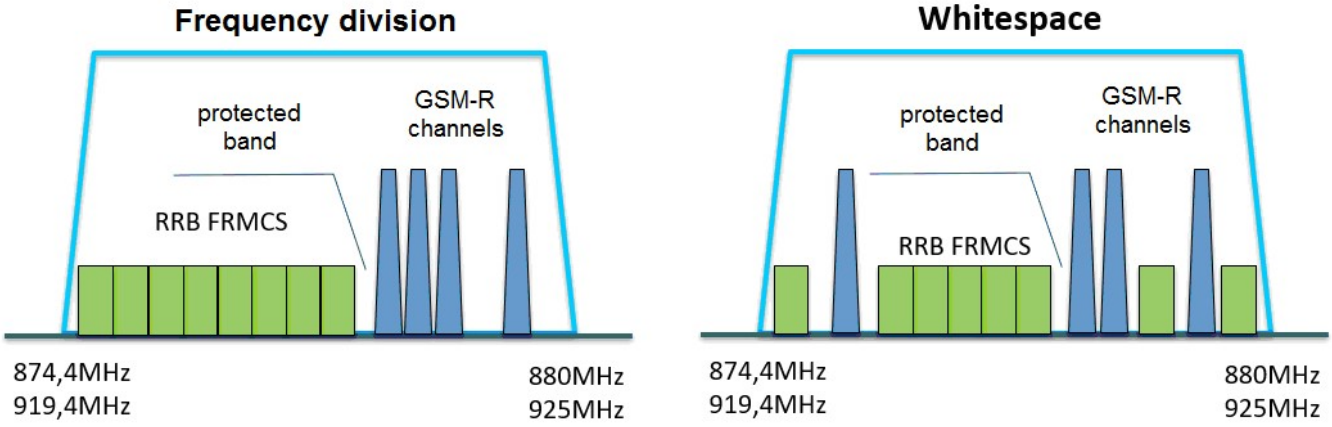
2.1.3 Coexistence of GSM-R and 5G/FRMCS in the band

The original usage plan, cited in [5], would allow the new extension to operate a full LTE channel with a width of 1.4MHz including a 0.1MHz separation from the existing GSM-R band. **The UIC's decision to use only 5G technology for European implementations makes such coexistence impossible, as the minimum 5G channel width is higher under current 3GPP standards.**

The scenario with simultaneous use of the 900MHz band for both systems has two basic variants under these conditions [7]:

- frequency division of the band into a part retained for GSM-R operation (with regard to the influence of different adjacent bands, a continuous allocation at the upper end of both paired bands) and FRMCS (the rest at the lower end of the bands including a new 1.6MHz extension)
- overlapping operation of both systems in the same band. Thanks to advanced 5G NR modulation techniques it is possible to use non-contiguous sections of the band in a specific location not occupied by GSM-R traffic (so-called whitespace).

Figure 1 - Variants of 900MHz band sharing



Splitting the band (frequency division) into contiguous parts for GSM-R and FRMCS has these limitations and operational implications:

- The bandwidth allocation for FRMCS is limited by the bandwidth that must be retained for GSM-R operation. The usual result of radio planning is the need for a minimum of 10 channels (low-traffic secondary lines), but typically 12-14 channels (normally busy lines), including the 2x100kHz separation band, i.e. a minimum of 2.2MHz, but most administrators have in the past used all of the original 19 channels, i.e. 4MHz, in their planning.
- This leaves a bandwidth of 1.4 - 3.2MHz (maximum 15 RRB) for FRMCS operation, which is smaller than the 5G NR standards supported by 5MHz. To operate in narrower bands, changes to 3GPP standards are required, which were worked on by 3GPP WG4 (network infrastructure) and WG5 (terminal). This resulted in the definition of a new modulation scheme for the 3MHz channel in the Rel18 specification.
- In most networks, such a split will need a re-planning of GSM-R, which is highly likely to trigger coverage measurement campaigns and the need for re-approval including the GSM-R deployed ETCS application which will introduce additional costs and time delays and create a bottleneck e.g. due to lack of qualified staff. Nevertheless, the scenario foresees changes throughout the migration period, where the GSM-R allocation will be gradually reduced as the traffic volume moves to FRMCS. However, it is not possible to estimate the progression of this migration more precisely, as the conditions of GSM-R and FRMCS coexistence, according to the current CCS 2023 TSI, allow users to split traffic between the two networks (e.g. ATP/ETCS on FRMCS, while leaving the call service on GSM-R).

Whitespace (overlay sharing) is being developed by ETSI‘s Technical Committee for Rail Telecommunication (TC RT) as an initiative of Kontron. The FRMCS system in it

- uses a 5MHz bandwidth allocation at the lower edge of the n100 band, but it is not continuous. The local configuration of the gNB omits the channels used by the collocated GSM-R base station, including the necessary bandwidth for protection. The possibility of such a deployment has so far been confirmed by ETSI TC RT tests on 4G LTE technology, but is expected to be confirmed also for standard 5G NR R17 modulation techniques, specifically in tests within the 5G-RACOM project, scheduled until 2025.
- Minimal interference between the two systems can be achieved if the signal strength of both is comparable at each coverage point. This implies the need for collocation of gNB FRMCS with a GSM-R base station, with approximately equal EIRP for both transmitters.

Table 3 summarises the main differences between the two variants of coexistence:

Table 3 - Main differences in the envisaged ways of sharing the 900MHz band

Band splitting (frequency division)	Overlay sharing (whitespace)
For FRMCS narrow channel (RB): max. 3.2MHz	For FRMCS full channel (RB): 5MHz
Requires 5G NR Rel18	5G NR Rel17 will suffice
EIRP determined based on 3GPP work	EIRP within narrow limits equivalent to GSM-R
Contiguous band allocations for FRMCS and GSM-R	Overlap, band for FRMCS incoherent
Configuration of gNB solved in the area	Configuration of each gNB individual

2.2 1900MHz band usage

Designated by CEPT as band n101 (but commonly referred to as 1900MHz TDD), this band is newly allocated for exclusive use by railway communications from 2021. The band is not yet allocated for railway radio communications in the Czech Republic. The entire 1900 - 1920MHz band is **currently allocated for mobile service, short-term or experimental use** in the Czech Republic**.** It will be allocated for railway radio communications from 2025, when IM may request it on the basis of strategic and economic considerations**.**

The band’s main differentiating factor is the use of time-division duplex (TDD). That has the following specific limitations and operational implications - not only for the migration phase, but for the entire duration of band use:

- Neighbouring network cells require mutual synchronisation (time and frame) to avoid interference, even between neighbouring cells of different networks. Synchronisation involves adjusting the duplex ratios (schemes) of neighbouring cells or, conversely, fully isolating cells when the duplex scheme is fundamentally changed, which limits the otherwise high flexibility of capacity allocation between uplink and downlink.
- The coverage (range) is smaller due to the much higher frequency and requires densification of gNB sites compared to the 900MHz band (and the existing GSM-R system). Also, radio planning in this band will be more complex because, as with the 900MHz band, it is no longer based on receiver level limits and involves the selection of MT transmit power. The gNB densification is therefore not across the board, but only applies to existing cells with high inter-site distance (i.e. cells in open countryside with low existing traffic load). The conditions are discussed in more detail in Chapter 2.2.1.

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

- Increasing capacity in areas of higher demand, such as large rail lines and hubs, dense urban networks or geomorphologically complex areas with increased need for coverage. Such a situation often arises in large nodes connecting individual lines served in the 900MHz band (e.g. for ETCS L2), where coverage can be provided separately in the 1900MHz band, or even overlaid with FRMCS deployed in the 900MHz band;
- on the border of a network that still uses the 900MHz band for GSM-R without the possibility of coordinating the use as defined in Chapter 2.1.3. In this case, the border sections may be covered in the 1900MHz band to avoid interference.

For the sake of completeness, it should be noted that there are also situations where it is required to cover the 1900MHz area network by installing in the 900MHz band, such as places of insufficient coverage due to the impossibility of adding passive infrastructure (mast) or covering tunnels with various repeater-based technologies that cannot propagate the signal in this band or provide the necessary synchronization for TDD.

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

- The allowed EIRP transmit power for base stations (gNB in 5G terminology) without coordination with other networks is up to 65dBm at 10MHz channel width. It is theoretically possible to allow higher powers on a national basis, but only with coordination with the networks concerned.
- Where specific coordination at the network boundary is not possible, ECC Report 353 and the related Recommendation ECC 23-01 set the default TDD framework structure and field strength at the boundary location.
- The permitted transmit power EIRP for on-board MT is up to 31dBm with an attenuation to the adjacent channel (ACLR) of at least 37dB, for handheld terminals 23dBm or 30dB. In both cases, the MT shall have transmit power control functional and activated.

The following factors are decisive for the final effect of the introduction of the 1900MHz band:

- The achievable communication rate for this TDD band is determined by
  - the set UL/DL RRB ratio (compared to MNO networks atypically set in favour of uplink in ratios of 50:50 to 90:10)
  - the overlap of bandwidth used in neighbouring cells (statically configured or dynamically applied only at the coverage boundary)
  - the MIMO scheme (with different effects in UL and DL)
  - and others;
- If both neighbouring networks choose to use the 1900MHz band, they must also address mutual time synchronisation and coordinate TDD duplex patterns to avoid interference in border areas. The procedures for such coordination are further addressed in documents issued by the UIC UGFA;
- It is necessary to densify the gNB (reduce cell diameters) in a certain ratio compared to the 900MHz band (n100), although not directly determined by the frequency ratio.

2.2.1 Signal propagation conditions

Modelling in three different simulation tools as well as for the 900MHz band (see Chapter 2.1.2), [3] shows the following conditions for the 1900MHz band:

- The 1900MHz band has been shown in simulations to be more sensitive to MT motion (Doppler effect) than the 900MHz band.
- Compared to the n100 band (900MHz), the simulations showed higher antenna gain at 1900MHz and significantly lower attenuation (by 5dB) at the cell edge in open terrain (due to NLoS propagation).
- The impact 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 benefit for uplink parameters, while for downlink they were clearly counterproductive (higher directivity of the transmit antenna due to the cap on EIRP limits the overall transmit power). The same results regarding MIMO are given by simulations for the open landscape, and also urban environments.
- Uplink has significantly worse parameters in urban environments and is significantly affected by the transmit power, so MTs with transmit power of 31dBm are practically usable. The situation is similar in downlink for large cells in open countryside (8km diameter in the simulation), where transmitting gNB with the maximum allowed 63dBm EIRP is essential.
- In the 1900MHz band, using TDD, the out-of-band spectrum mask configurations for uplink and downlink cannot be separated, and therefore the mask will be a compromise requiring further research and testing.
- In most of the simulated scenarios, the limiting factor was interference at the cell edge, so the mitigation features implemented in 5G are central to the operation. However, static frequency allocation between pairs or triplets of adjacent cells limits the transmission rate throughout the cell, so here too the use of dynamic techniques was found to make more sense.

An exemplary illustration of the FRMCS transmission conditions is the result of preliminary planning for the area near a railway station. The signal level for FRMCS (SS-RSRP) at the cell boundary for this band was -120dBm and for SINR up to -5dB in some places. Here again, the planning result confirmed the generally accepted rule of thumb that base station (gNB) densification, i.e. reducing the inter-site distance between base stations, will be necessary when moving to the 1900MHz band, and FRMCS capability is critical, especially for transmitting in the uplink direction.

The results of the preliminary radio planning for the line Brno - Breclav - Slovak border - Kuty - Bratislava, described in [25] part C, give an idea about what is needed to fulfill the conditions of 1900MHz band coverage from the locations of existing GSM-R base stations. There are 23 GSM-R base stations on the segment which has a total operational length of 133km. The system

on the Czech side, is in operation; on the Slovak side, parts are still in planning. (The coverage also includes the base station CD31601 [Hrušky] in the 2nd corridor.) The average inter-site distance is 6.0km. For equivalent coverage in the 1900MHz band, preliminary planning indicates an additional 21 gNBs will be needed, densifying the network to an average ISD of 3.2km. The increase in the number of base stations (gNBs) for this band would therefore be 91%. However, 8 of these sites are covered by MNO masts in the nearby 1800MHz band (see Chapter 2.3 for more details). Therefore, there is a chance for FRMCS to share in the use of the MNO infrastructure. The increase in the number of base stations (gNBs) structurally provided by IM would then be only 56%. Even if passive infrastructure sharing is implemented between SŽ and MNO, deploying FRMCS in the 1900MHz band will represent a non-negligible cost in the construction phase.

2.2.2 Interference with neighbouring bands

Despite the restrictive conditions for transmit power in the band, there is interference with adjacent allocated bands: 1805 - 1880MHz (downlink of n8 band) and 1920 - 1980MHz (uplink of n1 band). These are used by LTE MNO systems with FDD and 5MHz channel width [4] [5].

- The main reason for the impact on operation in these bands is that even the basic (uncoordinated) base station (gNB) FRMCS transmitter mask assumes higher receiver selectivity in the affected bands than today's Harmonized European Standards require (see also [5]). It can be assumed that the higher selectivity requirements will eventually be reflected in the Harmonised European Standards. Meanwhile, operators of mobile networks in the 1920 - 1980MHz band which do not comply with this condition will make adjustments to their equipment against possible interference only after agreement with the IM, because Czech legislation does not allow the assumed procedure only on the basis of a notification call to the IM.
- On the other hand, FRMCS vehicle station (generally MT) receivers must be sufficiently robust against transmitters of networks operating in the band up to 1880MHz, and base station (gNB) receivers against MT transmitters of these networks operating in the band above 1920MHz.
- In the 1880 - 1920MHz band, spectrum harmonisation for use by force component drones (UAS) is expected, with a possible impact in the form of changes to FRMCS requirements.
- In close proximity to the n101 band there are also allocations for the operation of DECT networks (1880 - 1900MHz). Systematic interference is not expected in this case due to the sporadic use of the DECT band and its Dynamic Channel Selection (DCS) algorithm. Therefore, mitigation measures will only be necessary in exceptional cases, e.g. dispatching facilities in the perimeter of a railway junction.

2.3 Possibilities of using the MNO bands

The phrase "MNO bandwidth use" for railway applications refers to the use of an MNO's network resources for railway communications. This can serve a variety of purposes:

- To be used as **a core communication system for critical services.** According to [5], in such cases the corresponding part of the MNO network must meet the railway's strict requirements for coverage, service availability, performance, border crossing/roaming conditions, QoS support levels (including prioritization and preemption of communications), cybersecurity, maintenance and SLAs, as evidenced by certification. Today's MNO networks typically do not meet these requirements.
- For use as **backup channels for critical communications.** Essentially the same requirements apply as in a core system, but with lower performance standards. Border crossing/roaming requirements can be applied to input and output to the IM network operating in paired RMR bands.
- MNO networks that do not meet these requirements can only be used **for non-critical (and currently non-interoperable) communications**. This is already represented by the current use of 4G LTE technology in public MNO networks.

Responsibility and decision-making authority for the utilization of MNO bands for critical applications - and even for FRMCS - is in principle up to the EU's individual Member States. The current V1 FRMCS standards (within the CCS TSI 2023) do not yet provide any guidance. EU countries have so far established rules for the RMR licensing of reserved railway rights-of-way. The current situation in the Czech Republic is described in the discussion of these rights-of-way in Chapters 2.1 and 2.2. The use of a specific band (not only RMRs) for railway applications is further limited by

- **coverage of the rail network** with a signal of sufficient quality for the application;
- in the case of own technology operation**, the operating costs;** in the case of roaming or a multi-operator core network (MOCN), the **agreed terms, conditions and usage tariffs;**
- **interference** with networks in the RMR bands (both FRMCS and GSM-R), including networks beyond the railway infrastructure itself, and undesirable coupling of antenna systems on the vehicle roof.

The state of coverage of the main railway lines in the Czech Republic is represented by the result of preliminary radio planning and the subsequent verification by measurements for the line section Brno - Breclav - Slovak border - Kuty - Bratislava, carried out within the study [25] part C. Coverage simulations were carried out within the framework of radio planning by one participating MNO for the 700MHz (n28) and 2100MHz (n1) bands and verified by measurements for the 700MHz (n28), 800MHz (n20) and 1800MHz (n3) bands. Over 80 existing base stations in the vicinity of the line were included in the simulation. The following table expresses the measurement results for all operators in terms of the percentage of measurement samples falling within the indicated RSRP ranges:

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

Range of the RSRP	-130 to -104dBm	-104 to -90dBm	more than -90dBm
700MHz band (n28)			
Czech side, 2 operators	21 - 94 %	6 - 24 %	0 - 54 %
Slovak side, 1 operator	5 %	31 %	64 %
800MHz band (n20)			
Czech side, 3 operators	0,2 - 0,4 %	7 - 12 %	88 - 93 %
Slovak side, 2 operators	3 - 4 %	28 - 30 %	67 - 69 %
1800MHz 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. Only the Slovak side in the 1800MHz band showed a worse situation. Specifically, the 700MHz band is effectively covered by only one operator on the Czech side, and the 1800MHz band by all of them poorly, while in Slovakia the 1800MHz band is not covered with good quality by any operator. The planning identified a total of 4 sites for coverage in the 700MHz band and another 13 sites for coverage in the 2100MHz band.

The strongest **inter-network interference in the RMR bands** is between a transmitter in the MNO band (uplink) and a receiver in the RMR band (downlink) when these are installed in close proximity to each other and operating simultaneously on a vehicle. In such a situation, spurious or out of band emissions from the MNO transmitter must not block or interfere with the RMR receiver. Table 5 summarizes for each MNO band the combinations requiring specific measures on the vehicle according to [30], since antenna spacing on the limited space of the vehicle roof cannot provide the necessary suppression.

Table 5 - Overview of MNO bands relevant to rail use

Interfering MNO band		Disturbed RMR zone	Minimum required suppression	Use in the Czech Republic
Mark	Range of frequencies			
n28	703 MHz - 733 MHz / 758 MHz - 788 MHz	Both	small (>20dB)	LTE, 3 MNO allocations of 10MHz each
n20	832 MHz - 862 MHz / 791 MHz - 821 MHz	Both	small (>20dB)	LTE, 3 MNO allocations of 10MHz each
n8	880 MHz - 915 MHz / 925 MHz - 960 MHz	900MHz	medium (>43dB)	in the Czech Republic, allocation only for 2G
n3	1710 MHz - 1785 MHz / 1805 MHz - 1880 MHz	1900MHz	medium (>43dB)	LTE, 3 MNO allocations 20 - 28MHz
n1	1920MHz -- 1980MHz / 2110MHz -- 2170MHz	1900MHz	high (>72dB)	LTE, 3 MNO allocations of 20MHz
n7	2500 MHz - 2570 MHz / 2620 MHz - 2690 MHz	1900MHz	medium (>43dB)	LTE, 4 MNO allocations 10 - 20MHz
n78	3300 MHz - 3800 MHz (TDD)	1900MHz	medium (>43dB)	allocation of part of band 3 MNO 100 - 160MHz

The mutual influence is described in more detail for the n1 and n3 bands in Chapter 2.3 and for the n8 band in Chapter 2.1.2. The MNO bands n28 (700MHz) and n20 (800MHz) do not significantly affect traffic in the RMR bands.

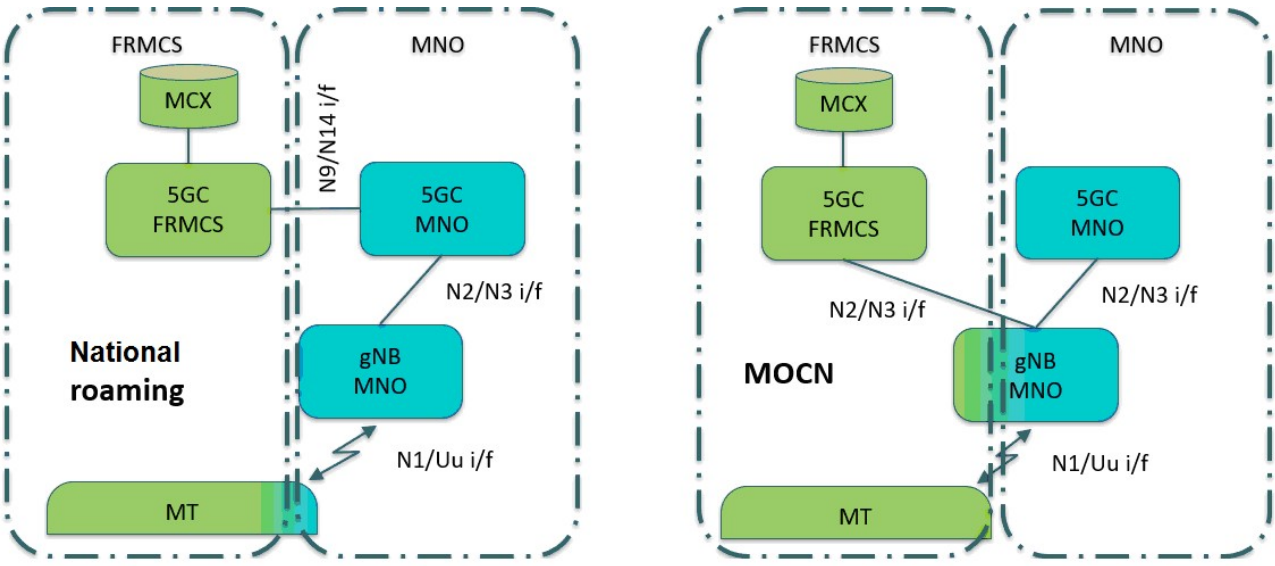
2.3.1 Network sharing schemes

Operational use of the MNOs' RAN infrastructure by IM is technically possible at two levels:

- **National roaming** is a scheme in which the IM operates part or all of the 5G core. Field terminals on vehicles are equipped with an IM SIM and are registered as visiting in the MNO network. Traffic is routed through the MNO's core to the IM's 5G core as a foreign network. The disadvantage of this arrangement is the mediated connection between the 5G RAN and the IM 5G core, which does not have full control over the QoS provided to the individual services. The national transition between the MNO and the IM (its own RAN in RMR bands), accompanied by e.g. IP re-assignment of the MT and new authentication, is also complicated.
- **MOCN** (Multiple Operator Core Networks) or **RAN sharing** works with the 5GC IM self-transmission connection directly to the gNB of the cooperating operator. gNB for communication offers in parallel the PLMN ID of the MNO and IM and a common list of neighboring cells. The ability to connect to them is determined by subscriber permissions. IM terminals communicating in this architecture logically remain in the FRMCS domain even if they are physically connected via the MNO gNB.

The third most common way today is for IM to use the MNO network only as a user - on SIMs provided by the MNO, the IM or carrier runs communications against access points (APs) to its private network where the server resources implementing the service are located. This is how telemetry services based on IoT principles are typically operated today, e.g. collecting meter readings from vehicles or remote monitoring and control of vehicle secondary systems (TCMS). Without additional QoS measures, the QoS for these services does not go beyond normal commercial levels and is not sufficient for more demanding applications.

Figure 2 - 5G NR/RAN sharing options



Sharing RANs with MOCN principles can be considered a proven solution with concrete benefits [22]:

- The architecture required to implement MOCN is given by an open standard (namely 3GPP TS 23.251). The principles of sharing are based on more than 20 years of experience: MNOs have used them since the UMTS standard.
- Sharing the 5G NR RAN between IM and MNO reduces the cost of the most extensive, and therefore most expensive, part of 5GS. The result is not only financial savings, but more importantly, the potential to accelerate construction and deployment of the required services.
- MNO RAN typically operating in higher bands than RMRs can provide more peak transmission capacity than the IM's own RAN. Although MNOs are typically oriented towards maximum downlink capacity, sharing can help to better utilize the network by adding IM traffic with exactly opposite preferences.
- Specific network sharing schemes can increase service availability, although the most commonly reported Core and gNB private network fault elimination scheme may not be based on correct assumptions.
- The direct interconnection of the Core and RAN gives the IM the ability to directly control the QoS of end-to-end services, because the communication is not dependent on the availability and throughput of the Core MNO's transmission systems and elements, which are sized to a normal commercial level of service. QoS management mechanisms can provide prioritization using only 5G quality indicator tags, in the same manner as in RAN RMR, or use a portion of the RRB capacity allocated in the MNO RAN through slicing.

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

As examples of the successful deployment of MOCNs, the networks of security and emergency services set up in this way in some countries (FirstNet in the USA, Erilisverkot in Finland or the Radio Network of the Future in France) are usually cited. However, a similar deployment for railways must address the following differences:

- The operational interest of security and emergency services coincides with areas of higher population density that are densely covered by MNOs with sufficient capacity so that traffic on the MNO RAN can achieve the required QoS. However, such coverage is not sufficiently continuous to support critical railway applications. In fact, MNO coverage of railway lines, especially those with little traffic, is still low and economically uninteresting for operators. On main lines, it is addressed by development programmes such as the EU's "5G Strategic Deployment Agenda" with a plan to cover up to 75,000 km of main lines, and there sharing can have the expected effect. An example of such a situation, although currently planned as the sharing only of passive infrastructure, is in Chapter 2.2.1.
- Critical communications for security and emergency services are different in detail and often functionally simpler than for railway applications. While the first applications have already been addressed in the first phases of 3GPP standardization in Rel14, not all railway requirements will be addressed in the currently-under-development Rel19. The differences are of course addressed by a separate MCX Core IM, which is critical for functionality. But unlike the solutions for security and emergency services, specific products for FRMCS are not yet on the market.

The risks of using MOCN are mainly as follows:

- The MNO may fundamentally change the technical conditions of operation – i.e. the extent of the reserved system resources during reconfiguration or upgrade to versions of the standard that do not meet the requirements of the railway; or change of the conditions under which the various elements of the communication system were certified to change coverage, for operational or other reasons or in extreme cases.
- Planned shutdown of a shared technology or making its continued operation subject to untenable commercial conditions.
- The cyber security of the operator's shared resources will not be at the level required for critical infrastructure. In particular, the expected consequence of an attack on the shared NG RAN would be a Denial of Service (DoS), with a fatal impact on rail operations. Appropriate cybersecurity is therefore another parameter of the shared RAN, conditioning its use for MOCN.

2.4 Use of satellite communication

Satellite services providing online two-way communication for emergency and civil (commercial) use can be divided into

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

Other satellite services such as positioning and broadcasting are one-way services and therefore cannot be considered as communications for the purposes of the FMCS. This does not mean that they cannot be used in railway operations. GNSS is currently the main source of MT location information, according to the FRMCS SRS. Examples of such non-communication services are the EUSPA services, comprising the positioning service (GNSS, specifically the Galileo system operated by EUSPA) and the EGNOS service (augmentation system supplementing information to the basic Galileo or GPS services used to refine localisation) and Copernicus (satellite-based terrestrial tracking service) [23]. However, these services are not the subject of the present study.

2.4.1 Non-3GPP variants

Narrowband communication, originally intended for voice-call service to emergency forces, emergency communication, etc., has expanded over time to include commercial use in shipping, aviation and professional use in remote areas. Such services are generally not suitable for integration into FRMCS for several reasons:

- Specific services, such as category calls or text message transmission, use specific protocols that merge the different protocol layers, making them incompatible with the FRMCS architecture, which strictly separates the transport, service and application layers. The specific protocols may not fulfil all the requirements placed on FRMCS, such as QoS support or

service preemption, user and MT authorization, transmission security (e.g. for ETCS), latency requirements, etc. Such services can only exist outside FRMCS, connected by appropriate gateways.

- Narrowband transparent packet data transmission is not usable as a transport layer below the FRMCS/MCX service layer because its transmission capacity is not sufficient even for overhead data flows such as IMS/MCX signalling (control plane) or encryption redundancy.
- A series of projects checking the suitability of satellite systems for railway applications have so far demonstrated the lack of service availability on a moving vehicle, caused by shadowing by terrain formations and buildings, even for very narrowband systems such as GNSS.

Broadband satellite access is commonly offered as B2C Internet access with speeds up to 150Mbps with the usual limitations of this type of service - fixed-term contracts, Fair User Policy (FUP) after reaching the data limit (tens of GB per month), etc. [13]. The services of each provider differ in speed, latency, stability and, of course, tariff conditions. There are relatively few providers - (for North America) Starlink (LEO), Viasat and Hughesnet (GEO). The use of this type of satellite communication within FRMCS is hindered by

- absolutely minimal - and for MCX/FRMCS, insufficient - means of service management (session management, QoS support, security).
- the use of fixed parabolic antennas up to 0.75m [31], which are not installable on the railway vehicle. As with narrowband receivers, transmission is most likely not prepared for the rapid leakage or Doppler effects caused by MT movement and shadowing by terrain formations and buildings.

2.4.2 5G satellite communications

Satellite communications have been developed within 3GPP since Rel14 and the first studies for Rel15 standards, mainly as an alternative to terrestrial RAN (4G LTE and 5G NR) for areas not covered, or for which terrestrial coverage is uneconomical (e.g. sparsely populated areas), and for critical communications (among others) as links with greater resilience than terrestrial infrastructure [12]. As it has been progressively standardised since Rel17 [14], it fulfils the requirements of IMT-2020 mobile communications according to ITU-R. The application of satellite access for critical (MCX) services is being prepared for the next release (i.e. Rel19) onwards. Satellite communications are expected mainly to benefit critical services and industrial applications requiring continuous coverage. Within the framework of the UIC FRMCS FRS and SRS standards, it can therefore be considered as one variant of the 3GPP approach and should therefore be used as incorporated in 5GS, in a realistic on-board implementation as a FRMCS gateway satellite radio module with direct communication to a satellite transceiver.

Other Rel18 use-cases - such as satellite backhaul to the terrestrial gNB, satellite access for IoT, satellite relaying of traffic between MTs, content distribution (broadcast/multicast), support for non-contiguous satellite coverage, edge computing on satellite, and traffic with routing between MTs directly to the satellite gNB (not applicable to the IMS/MCX service layer above) - are not relevant to FRMCS. Similarly, with respect to the mandatory inclusion of GNSS localization in FRMCS, mechanisms planned from Rel19 onwards to allow even MT connectivity without its support are not needed.

The 3GPP standardisation work relates more generally to Non-terrestrial Networks (**NTNs**), which are networks with communications assets deployed either on satellites with different types of orbit or deployed on heavier- or lighter-than-air unmanned aerial vehicles (**HAPS**) operating at altitudes of 8-50km. Within FRMCS, in the FR1 frequency range (0.4 - 7.1GHz), satellites in a low or very low Earth orbit (**LEO** or **VLEO**) of 500 - 2000km are of particular interest due to their low latency, as are geostationary systems (**GEO**) at an altitude of 35 768km, due to their maintaining position over the area to be served.

In 3GPP studies [12], and subsequently in the European Space Agency's SATis5 project [14], architectures with an access link between MT, satellite (HAPS converter) and ground base station (gateway) were developed in two variants:

- without signal regeneration (**transparent link**, bentpipe), in which only the analogue signal is processed on the satellite (filtering, frequency change, amplification), where it works as a Distributed Unit (DU) or Remote Radio Head (RRH) within the 5G NR architecture. This type of link is mainly used in GEO satellites and until Rel17 was the only one developed into specific standards.
- The alternative is a **non-transparent regenerative link**, where the satellite, in addition to the previous analogue operations, demodulates and decodes the signal, switches or routes it, and re-encodes and re-modulates it. Thus, the satellite performs the functions of a full-fledged gNB (DU and CU). This type is mainly used for LEO links in S-band (1 - 6GHz), where it allows the necessary retransmission of links (Inter Satellite Links, ISL) between satellites grouped in constellations of large numbers, only some of which are directly visible from the ground station providing the gateway to terrestrial networks. This type of link will be fully embedded in 3GPP standards from Rel19.

Bands up to 7.1GHz (in 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 with FDD operation:

Table 6 - Bands designated for railway satellite communications

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

The 3GPP study [12] and the more in-depth tests in the SATis5 project [14] have also revealed the main technical problems associated with the integration of satellite links into 5GS:

- The radio signal for all satellite links is more subject to atmospheric effects when passing through the ionosphere (up to 6GHz) or the troposphere (for frequencies above 6GHz and low elevation).
- Satellite signal coverage cells are many times larger than terrestrial cells and coverage is thus far more uneven than for terrestrial 5G NR. Cells can have a range that extends across national borders or specific networks, and a single cell can belong to several 5GCs with different commercial or even regulatory conditions of use. Because of these constraints, large areas typically have to be divided into smaller areas. In the physical layer, the partitioning is represented by radiation lobes, mapped in a logical configuration by virtual cells with a dimension similar to the cells of terrestrial systems, which facilitates the connection of the satellite RAN to the 5GC, as well as the standards required for a fixed tracking area.
- The use of GEO satellites is demanding, especially for solution of the link's physical layer. Due to the link's long distance, 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 that is not mountable on the rail vehicle. The transmission is not able to compensate for the rapid leakage caused by MT movement. Therefore, the links to GEO satellites are not used for direct connection to the MT, but for backhaul to secondary ground gNBs.
- The high latency of connections (several tenths of a second for GEO connections) not only does not suit some types of services, but also requires adaptation of some internal network control mechanisms, described below.
- For other types of satellites, their position relative to the Earth's surface changes over time, and this (predictable) motion must be compensated for by various means to minimize the handovers it forces. The satellite transmitter's coverage is either moving (along with the movement of the satellite) or the area covered is stabilised by beamforming as the satellite moves over the horizon. Controlling the transmission with respect to the satellite's motion to maintain coverage of the MT by a particular transmit lobe into which the covered area is divided, requires **knowledge of the position of the MT**, which must be ascertained by means outside the satellite system itself. The source of the position is, according to current standards, essentially a GNSS service with a required accuracy of about 2km, from Rel18 verified by 5GS itself with an accuracy of 5-10km using delay measurements. In this way, the satellite terminal determines not only its position, but also other parameters of the access satellite needed to establish a connection with random access medium (MAC): satellite orbit and time advance; traffic routing towards the 5GC (PLMN selection) and its accounting; support of emergency services, typically dependent on location; compliance with local legislation; etc.
- In addition, LEO satellites move at high velocities relative to the Earth's surface, which introduce additional effects: Doppler shift in frequency and rapid changes in delay.
- All of the described consequences of larger satellite distances and movements require **extensions to** the main radio interface protocols - Medium Access Control (MAC) layer, Radio Link Control (RLC) in the physical layer, and Packet Data Convergence Protocol (PDCP) - to provide additional information about the MT position and satellite orbit, enhanced cell identification, more complex handover control, modified HARQ timing or transmit power control, in order to deal with the consequences of satellite distance and movement, such as high latency or Doppler shift. For MT-terminated links, all these extensions must be supported directly by the MT.
- A consequence of the required mobility between satellite and other types of 5G access is the addition of some of the mentioned features (e.g. enhanced satellite cell localization in the neighbour list) to the protocols of terrestrial 5G NR. When satellite communication is used in FRMCS, these additions will have to be reflected in its technical standards and supported by MT on vehicles and possibly by other users.

Unlike RMR communications, satellite access will not be an IM owned/operated system, but will be purchased as a service from **commercial or public sector entities.** An extreme variant is the use of satellite links tied to **cloud** services, an example of which is Amazon's AWS-GSN ground stations in the US 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 in various programmes centred around the SATis5 demonstration programme, integrated under the ESA ARTES project [32], where railway applications fall under the use-case of satellite connectivity for moving MT (such as trains and specially VRT) [11]. This use-case has been addressed in 3GPP since Rel16 as Enhanced Mobile Broadband (eMBB) Communications on-the-Move (COTM) or High Reliability Communications (HRC, demonstrated using the commercial GEO satellite ASTRA 2F operated by SES) [14]. The latter use-case is associated with multiple connectivity over terrestrial and satellite networks. It is also usable for capacity augmentation or load balancing between networks. Planned communications of infrastructure elements (URS applications 6.10 and 6.12 - see Chapter 1.1) are represented by the use-case Massive machine type communications (mMTC) - Local area IoT services.

IRIS² (Infrastructure for Resilience, Interconnectivity and Security by Satellite) is an example of a satellite system operated partly by a public-law entity (by the EU). It is being built as a mixed system using LEO, MEO and GEO satellites, with the participation of ESA, EUSPA and the private sector (represented by a consortium of SES and Eutelsat operators) [17].. IRIS² is intended **primarily for use by government institutions** and force units within EUSPA GOVSATCOM [15]. This designation is also reflected in its technical characteristics: It will provide mainly narrowband services, strongly secured by EuroQCI quantum cryptography. However, the system is to **apply 5G NTN principles** to the maximum extent and its later commercial part envisages fixed and mobile broadband access services including services for the transport sector (details not yet specified), B2B communication links, and connection to cloud services [16]. Services for government institutions (Hardgov) are to reach full operation and global coverage in 2027.

The satellite access links in all these variants to the typically IM-owned 5GC will follow the scheme described in Chapter 2.3.1. The sharing of satellite RAN resources should, like the MNO terrestrial networks (Chapter 2.3) preferably be supported by a slice intended for rail usage or at least by roaming. The risks of using satellite links for IM are as follows, for different types of MNO interconnection according to Chapter 2.3.1:

- A satellite network operator providing only a service (own SIM) or roaming can fundamentally change the commercial terms of operation, in particular the price of the service, which is/will be several times the price of analogue terrestrial network services.
- A foreign satellite network operator may not offer sharing or roaming on acceptable commercial terms or at all.
- The operator of a satellite network providing roaming or cooperating on MOCN may change technical conditions - the extent of reserved resources of the system during its reconfiguration - or upgrade to versions of the standard that do not meet the requirements of the railway, or change the conditions under which various elements of the communication system were certified.
- The available commercial satellite RANs may not meet the requirements of the railway standards in terms of their parameters, in particular with regard to security, QoS management (including preemption) or coverage continuity (in particular for LEO networks, only a fraction of the target number of satellites are activated so far).
- For each service it will be necessary to individually assess the latency achieved. In GEO satellite access, tests on the SATis5 polygon showed values of over 200ms, which do not meet the limits for voice service and communication control (signalling) according to FRMCS SRS. Compliant values can only be expected for services based on LEO satellites. On the other hand, link throughputs of over 10Mb/s can be expected at channel widths of 15-30MHz and spectral densities achieved according to [32], i.e. comparable to the RMR bandwidths of the terrestrial system.
- As with narrowband systems and GNSS, a high degree of shadowing by landforms and buildings can be expected, which may prevent the use of satellite links in urban environments and station areas.
- Specifically in the Czech Republic, only the n256 band immediately adjacent to the n1 land mobile band is allocated for this type of satellite communication. It will be necessary to map the situation in neighbouring countries/networks to see if this band will also be used there and thus would be interoperable.

2.5 Non-3GPP technology

Other radio communication standards potentially applicable or historically used to support railway operations include narrowband terrestrial radio transmissions (analogue or digital), transmission technologies covered under the collective term WiFi, and non-3GPP type satellite links, already discussed in chapter .2.4.1.

The prospect of integrating narrowband systems into the 5G/FRMCS environment is very low:

- Analogue systems without other essential measures (specific gateways) are incompatible with the digital/packet environment. The benefit of such an integration is minimal because analogue systems basically provide only a call service or data transfers at speeds up to 5kb/s, which is useless in the FRMCS environment.
- **Digital narrowband standards** such as DMR, P25 or TETRA provide specific services, such as category calls or text message transmission, using specific protocols that merge the different protocol layers and are thus not directly compatible with the FRMCS architecture. At the service layer (MCX) level, they can be integrated through gateways standardised within the 3GPP MCX architecture (3GPP standard TS23.283 and downstream), which also provide the minimum necessary integration into service preemption mechanisms, user and MT authorisation, transmission security, etc. However, voice and data services have significantly lower functionality than native FRMCS MTs and will **never be fully interoperable**.
- The narrowband transparent packet data transmission provided by these systems is not usable as a transport layer below the FRMCS/MCX service layer because its **transmission capacity is not sufficient** even for overhead data flows such as IMS/MCX signalling (control plane) or encryption redundancy.

Wireless access (WLAN) systems, collectively referred to as **WiFi**, are systems standardized by the IEEE 802.11 suite of standards.They are designed primarily for terrestrial stationary access to packet services at the link level (LAN), maximally adapted to the downstream fixed network based on Ethernet standards (IEEE 802.1). Several generations of these standards are characterized by theoretical transmission rates of units up to hundreds of Mbps achieved by OFDM or similar modulation on channels 20 - 40MHz wide [18]. Because of such bandwidth, with exceptions, they are standardized for bands in the 2 - 6GHz range (FR2). For FRMCS communications [SRS1.2.0], WiFi bands are specifically expected to be used:

- 2.400 - 2.4835GHz,
- 5.150 - 5.350GHz, 5.470 - 5.725GHz and 5.735 - 5.875GHz
- 5.945 - 6.425GHz.

Due to these high operating frequencies, the high modulation density used and the resulting high required noise figure (SNR) and low transmit power compared to cellular networks, WiFi operates in both indoor and outdoor environments with a relatively short range of only hundreds of meters. The relatively high data rates of WiFi compared to NR communication in RMR bands (see2.6) can be beneficial for railway operations, but the use is limited to specific conditions:

- Because of the just-mentioned short range of WiFi communication, continuous coverage of a railway line is very problematic, even though some communication scenarios for VRT count on such schemes (implemented but instead of 5G NR in the 3.5GHz band). For conventional lines, however, the investment-intensive construction part will not be economically justifiable and WiFi APs will only be installed at gNB locations in RMR bands. **Coverage** will thus be **spotty, not exceeding 20% of the line length**, with periodic connection dropouts of tens of seconds. Such a communication environment **is not usable for critical applications,** and even non-critical applications must be prepared for intermittent service (by caching data for transmission, developing fast authentication and authorisation mechanisms, etc.). Some of these tasks can be taken over by WLAN management mechanisms [21], building on corporate and open standards, but the batch nature of communication in such an arrangement will be preserved.
- WiFi communication is designed for stationary or nomadic use. The specified range for outdoor environments typically applies to line-of-sight (LOS) links. Therefore, the link will be affected by **train movement** and associated Doppler shifts of the signal and rapid leakage. In particular, the WiFi transmission mechanism is not designed for the latter effect and the link performance will be severely degraded. Therefore, there may be a scenario where WiFi APs are only usable in locations with slow train speeds such as **large railway stations, marshalling yards and depots**. In such a case, the kilometre coverage of the line will be only fractions of a percent, although the time coverage will be more favourable - of the order of one percent. The specific application communication conditions mentioned above will be much more challenging in such a case.

It follows that communication using WiFi standards to vehicles may only be of **marginal relevance** to the railway environment for **selected non-critical applications**, amongst the applications classified according to FRMCS URS (see Chapter 1.1) e.g. Communication in stations and service facilities (6.8), Telemetry train communication (6.9), Data communication for train departure (6.18) or CCTV archive transmission (6.22).

2.6 Meeting communication requirements

The communication requirements for the applications needed during migration and for the target range of critical communications after transition to FRMCS are quantified e.g. by [5], based on the UIC model from 2018. Similar data for a narrower range of basic applications migrating from GSM-R – i.e. voice services, ATP/ETCS and ATO (to GoA2) - are also given by [8]. The requirements were quantified in 4 variants, of which only some are selected for the purpose of this study:

- **Pkg #2** - the full target set of applications according to [5], including mission critical video, which, while still not complete compared to the full USR requirements (see Chapter 1.1), covers well the part of them that is sufficiently defined by the

downstream UIC standards and is therefore of real interest to carriers and IMs. Although the full set considered theoretically in [5] without critical video is special - in that it is the only one that exhibits a high asymmetry in favour of UL and would be optimal to use TDD transmission with a UL/DL ratio of 90:10, i.e. in the 1900MHz band - it is not part of the most likely scenario Pkg #1R (with critical video added as an extension to Pkg #2) - for the latter, the asymmetry provided by the 1900MHz TDD band is not that significant, but it can be used with a different ratio setting, e.g. 70:30, to e.g. support the Pkg #2 target file.

- **Pkg #1** - application file required by [5] during migration from GSM-R.
- **Pkg #1R** - the same file, but reduced by the transmission capacity for the most demanding application of critical video (URS ch.5.27). Compared to the requirements estimate of the existing file operated on GSM-R (voice services, ATP/ETCS and ATO to GoA2) according to Annex [28], the required transport capacity is approximately double, because even without video, it includes applications operated today outside GSM-R (emergency calls to the public network, remote control of driving vehicles, basic vehicle telematics, etc.).

Table 7 compares these needs with the available 5G transport capacity, as quantified by the simulations in [3]:

- **Transmission capacity requirements** are quantified per train and per RAN cell. The traffic parameters (for the different segments considered, a RAN cell diameter of 8 km and a density of 0.33 to 0.67 trains per km, i.e. 2.6 to 5.4 trains logged per cell) roughly correspond to some simulation variants, but they only serve to calculate the total required cell capacity and do not affect the requirements of a single train.
- **The simulated transfer capacities**, on the other hand, strongly depend on the average of the cell and the number of trains logged in it. Therefore the average number of trains per cell in the simulation are shown in the table. However, the values chosen for the simulation correspond well to reality on the SŽ network, as they were quantified in more detail e.g. for the study [25]. There, traffic densities are close to 0.4 trains per km, and even the ISD cell averages are in good agreement: 4 - 9km for GSM-R (900MHz band), while the proposed values for 1900MHz are 1.8 - 4.9km.

For the values of available transmission capacity used in the comparison, the following applies:

- From the simulation results, the values of the 50% percentile of the transmission rate distribution, determined for a large set of trains moving through the simulated cells, are selected for comparison. It can be expected that a (moving) train will have at least this transmission rate available for half of the travel time. For completeness, the values at the edge of each cell type, represented in the simulations by the 5% percentile, are also shown. The average values of the transfer rate, which would be more relevant for calculating the volume of transferred data, are not included in the published simulation results.
- Achievable speeds are taken everywhere for settings with the maximum allowed transmit power (uplink up to 31dBm, 1900 MHz downlink 63dBm, 900 MHz downlink 46dBm). In locations where coverage conditions are more favourable, the downlink transmit power can be reduced. The uplink power will be reduced automatically by mandatory control.
- From the simulated MIMO variants, those most likely to be implemented on vehicles in conjunction with GSM-R according to [8] were selected for comparison. The limitation here is mainly on the vehicle side, where, due to space constraints, more than 2 antennas cannot be assumed, only one of which is a transmitting antenna within the Rel18 standards. MIMO schemes are therefore limited to 1xN for uplink and Nx2 for downlink. Since simulations in [3] showed minimal benefit of Nx8 configurations, the number of antennas per gNB is also limited to 4. As a result, the MIMO configurations chosen to estimate the achievable throughputs are 1x4 for uplink and 4x2 for downlink (or 2x2 where it gives better results).

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

Required capacity for a single train	Train/cell	Uplink [Mbps]	Downlink [Mbps]
Pkg #1R	up to 6	0,19	0,2
Pkg #1	up to 6	3,49	3,5
Pkg #2	up to 6	7,42	4,38
Achievable capacities in the 1900MHz band			
in open countryside, ISD 8km	4	1,3 - 2,2/2,3*	0,2*/1,2 - 3,3
on the edge of such a cell	4	0,4 - 0,8/1,4*	0,2*/0,8 - 1,2
in open countryside, ISD 4km	2	4,3 - 5,4/10,0*	1,2* - 6,0
on the edge of such a cell	2	2,9 - 3,3/6,2*	0,4* - 1,8
in urban environment (built-up area), ISD 2km	2	1,4 - 4,6/8,6*	0,4*/2,2 - 8,7
on the edge of such a cell	2	0,5 - 1,6/2,9*	0,3*/1,3 - 3,5
Achievable capacities in the 900MHz band			
in open countryside, ISD 8km	4	2,1 - 2,5	2,2 - 3,0
on the edge of such a cell	4	1,0 - 1,6	1,1 - 1,4
In urban environment (built-up area), ISD 4km	4	0,7 - 1,7	1,0 - 2,7
on the edge of such a cell	4	0,2 - 0,4	0,4 - 1,1
In urban environment (built-up area), ISD 2km	2	2,5 - 4,6	2,6 - 6,1
on the edge of such a cell	2	1,6 - 3,3	0,8 - 2,1

Note: values marked * in the table are based on simulated DL/UL multiplex ratios of 90:10.

Although the values of achievable transmission rates show large variance in the different simulation methods, the following conclusions can be drawn from the table:

- **In the initial phase of migration**, FRMCS will be able to provide the capacity required for the applications in all operational circumstances in the frequency range supported today by GSM-R (i.e. with requirements less than Pkg #1R's), in which IMs (including the Czech one) plan to migrate. Contrary to general expectation, this also applies to 1900MHz cells with 8km ISD, i.e. 1900MHz operation on an unthickened gNB network
- However, with **deployment of the first critical video applications** (Pkg #1)**, we can already expect limitations** at the edges of the cell, manifested in the case of a moving train by congestion and instability of the link, or at best by fluctuations in transmission latency at time intervals that will not be acceptable to the exploiting application. The situation will be worse in the 900MHz band, where even a gNB network with an ISD of 4km (i.e. densified relative to GSM-R), may not meet these requirements, especially in the uplink. In the 1900MHz band, the capacity can be optimised by setting the DL/UL multiplex ratio appropriately, but the extreme simulated ratio of 90:10 (values marked * in the table) disproportionally reduces the guaranteed downlink capacity and is therefore not a universal solution. The arrival of additional applications, represented by Pkg #2, will further aggravate the situation and only special cases (in the table the underlined field) will be able to meet the requirements. The only solution then will be to split the communication into multiple bands using Multipath / Application specific path selection techniques according to [30], implying the existence of an overlay network in both RMR bands or the transition of part of the traffic to MNO networks, even for critical traffic, since Pkg #2 from non-critical applications includes only telemetry and remote control of on-board technologies (URS ch.6.9 / 6-11). The addition of selected MNO bands to the FRMCS specifications (primarily TOBA) must occur in FRMCS V3, as their use must be interoperable to support critical applications.

3 Possible migration scenarios

The time frame and need for existing mobile railway communications to migrate to newer technologies are determined by support for GSM-R terminating after 2035, when according to [1], the biggest problems will be the availability of qualified personnel and the acquisition of replacement hardware to maintain network operation. At the same time, the cornerstones for FRMCS as aa successor technology - the allocation of reserved bands (RMR) recommended by the ECC, and the 2023 update of the CCS TSI to include FRMCS V1 standards - have been laid.

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

- GSM-R based services must be available for the entire planned duration of the transition while maintaining the original coverage and quality. Termination and/or major reduction of operation must be notified by IM to the affected carriers with a relatively long lead time as specified by legislation in the CCS TSI.
- The proportion of vehicles communicating within a particular standard is always higher than the proportion of that standard in the infrastructure. This is true for both the FRMCS system being deployed and the GSM-R system being replaced. The consequence of this is that a certain proportion of vehicles communicating in both standards will be needed when the vehicle migration and infrastructure migration overlap in their timing.
- FRMCS communications can share the 900MHz band with GSM-R (details are discussed in Chapter 2.1). FRMCS can also be deployed in the 1900MHz band while maintaining the full extent of GSM-R operation in the 900MHz band until GSM-R use terminates (a variant discussed in detail in Chapter 2.2). Various combinations of these solutions can be deployed, possibly also using MNO bands temporarily or permanently for critical applications.
- The length of the migration period is influenced both on the IM side (by the time needed to construct the ground part of the system) and on the carriers' side (by the pace at which new on-board parts of the system are installed), as well as by the commercial availability of the necessary components, the installation, construction and workshop capacities, the availability and amount of funding, and the operationally acceptable extent of vehicle shutdowns for the necessary modifications. In the first case (the construction part of the system), the extent to which existing passive infrastructure can be used is crucial. In the second case, the financial and time costs to approve the type changes required by the installation are significant and are likely to increase as the approval process moves to ERA. Some of these mentioned factors are interdependent, e.g. acquisition costs typically increase as the required deadlines near.
- The pace of introduction (or an increase of need) for new applications that cannot be covered by the GSM-R system or other existing means of communication for various reasons. These will not be included in the migration from GSM-R to FRMCS. They will be integrated into FRMCS only in subsequent stages.
- The legislative condition is fulfilment of the requirements of the CCS Annex I TSI §7.3.1.2, according to which the termination of operation on individual sections must be notified to IM **by entry in the RINF (Register of Infrastructure) five years in advance**.

The preferred length of the migration period for each entity depends on the potential or preferred cost mix:

- **A longer period of time** is more advantageous in terms of investment. The volume of investment per year may be limited by various factors. The acquisition costs of the technologies, as well as their installation and commissioning, and possibly the construction phase, increase as the construction timeframe shortens due to the reaction of manufacturers and suppliers to the demand overhang, higher utilisation of limited installation capacities, etc. In the case of HV equipment, this is compounded by a larger proportion of the fleet being renewed during longer migrations. The cost of communications equipment for new HVs is normally not included in the cost of technology replacement.
- **A shorter period** is preferable in terms of operating costs**,**. This is particularly pronounced for those entities that build and gradually commission their part of the system ahead of time in each scenario and bear the double operating costs of the old and new technology for the rest of the migration.
- **An earlier start and end of the migration period is beneficial for both sides**. Firstly, during the decline of GSM-R technology on the suppliers' side after 2030, a significant increase in GSM-R operating costs is expected (mainly attributable to purchase/pre-stocking, storage of spare parts, and support services from manufacturers). For networks in which the

planned GSM-R coverage will not be completed at the start of the migration, there is the added saving of non-recoverable investment in short-term GSM-R components, most of which will not be usable under FRMCS.

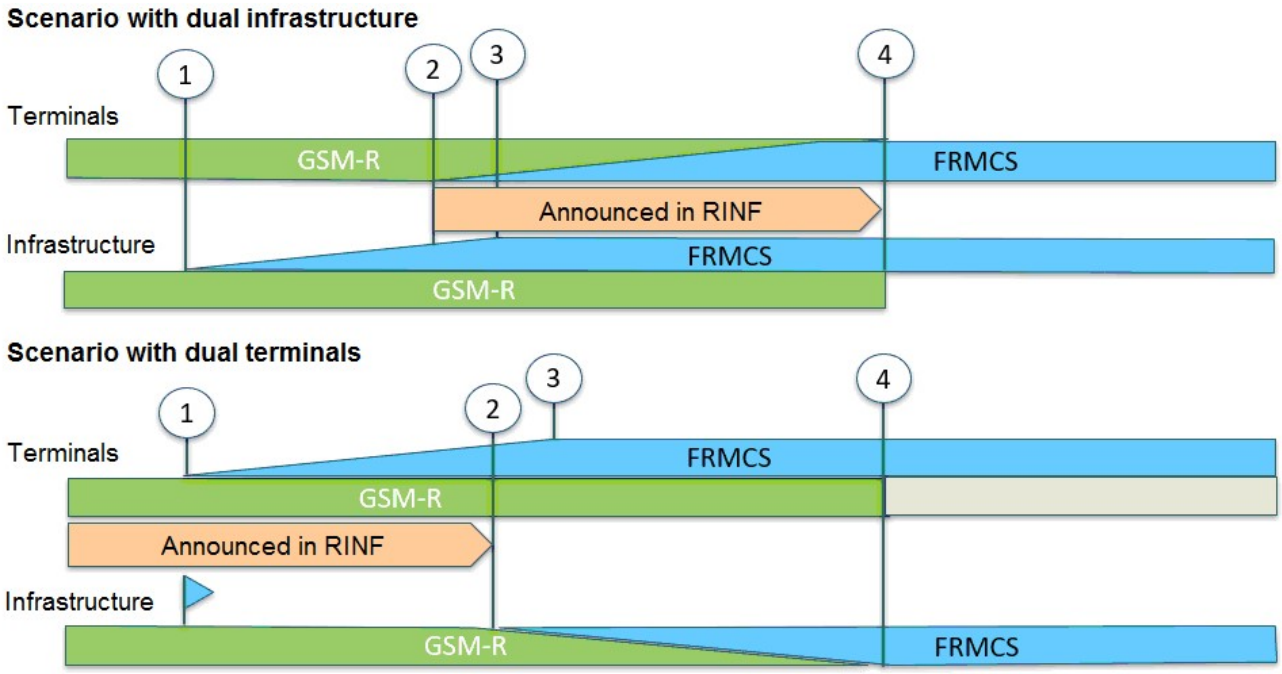
3.1 Theoretical scenarios

At the request of ERA, possible migration scenarios were studied as early as 2015 [2], i.e. at a stage when the basic technical characteristics of the successor FRMCS system, the bands used, and the detailed network architecture were not yet known. Different variants of the two basic migration procedures were evaluated with an economic model against the "no change“ option:

- One scenario, in several variants, was a process with a relatively long **overlap of both systems on the infrastructure**, during which carriers gradually implement the new technology on vehicles and other terminals used by workers (mobile handhelds) or infrastructure (stationary);
- Another scenario was the **dual terminal** approach, in which the infrastructure technology is upgraded locally or network-wide (depending on the specific variant) in a short period of time - essentially a switch from one technology to the other. In this case, carriers equip their vehicles in advance with terminals capable of communicating in both standards and are therefore able to use them on both upgraded and non-upgraded parts of the network. This baseline option also includes the option of changing the terminal technology in parallel with the infrastructure (in the short term, in very close coordination with IM), which proved unrealistic when considered further.

The two scenarios were studied as blankets – that is, applied homogeneously on the infrastructure on all line sections according to the respective timetable. In addition to these area-based approaches to migration, there are also approaches using different site-specific procedures. These include, for example, the docking of 900MHz islands with 1900MHz gNBs or 1900MHz transition sections at domain boundaries, examples of which are given in Chapter 2.2 [7]. For this purpose, the scenarios did not include preparatory steps such as polygon tests, pilot carriages or replacements of Class B communication systems, which are typically part of railway entities‘ specific scenarios.

Figure 3 - Basic theoretical migration scenarios



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

1: Initial stage - infrastructure and carriers use GSM-R operationally. IM is building FRMCS in advance on all or part of the network, but can only put it into operation to the extent necessary for testing and preparation for vehicle migration: piloting, testing and type approval. Carriers may use this time for commercial and technical preparation for subsequent vehicle retrofitting (supplier selection, prototype builds and testing).

2: IM launches FRMCS on all or a significant part of the network, but the GSM-R infrastructure remains operational. At this latest step, the IM shall announce the first dates for the end of GSM-R operation according to CCS TSI Annex I §7.3.1.2. The cost of keeping GSM-R in service during this step is expected to increase gradually, with the rate of increase increasing towards the announced end of support in 2035.

3: IM completes the construction of the FRMCS infrastructure, which the upgraded vehicles and terminals use without restrictions. GSM-R support is no longer required on them. The cost of maintaining the IM GSM-R run-off system continues to increase at this step.

4: Re-equipment of the relevant carriers' fleet is completed. All vehicles use the FRMCS infrastructure. IM is discontinuing GSM-R operation as it is no longer used. CAPEX of FRMCS remains at a certain level at this step by building/equipping additional lines or equipping new vehicles.

Migration using dual terminals includes the following steps:

1: Preparatory stage - the infrastructure and the carriers are using GSM-R operationally but IM is stopping its development. IM had to announce well in advance the first dates for the end of GSM-R operation according to CCS TSI Annex I §7.3.1.2. During this step, all preparatory phases of re-equipment - such as supplier selection, prototype builds and type approval - must take place. The IM must ensure minimum conditions for this by building a sufficient FRMCS pilot section for testing.

2: Start of FRMCS construction - a significant number of vehicles are re-equipped with the new FRMCS. The IM starts to commission the FRMCS, usually in parts of the network, and ceases GSM-R operations in those parts. The number of unequipped vehicles decreases sharply (the proportion of vehicles equipped with FRMCS must generally be higher than the proportion of FRMCS in the IM network).

3: Carriers finalize the outfitting of vehicles to support FRMCS. IM continues to rebuild infrastructure to support FRMCS. In the upgraded portion of the network, carriers use the FRMCS infrastructure for which their vehicles are already equipped. The cost of maintaining the GSM-R system at this step is expected to increase gradually, with the rate of increase increasing after the announced end of support in 2035.

4: IM completes construction and commissioning of FRMCS over the entire network and ceases GSM-R operations. The CAPEX of FRMCS remains at a certain level at this step by constructing/equipping additional lines.

The implementation conditions and outcomes of these scenarios differ in many aspects:

- The timing and conditions under which the IM must announce the **GSM-R termination dates** as required by the CCS TSIs in Annex I, §7.3.1.2. - In each migration procedure there must be **time margins** to meet the required 5-year advance notification period. Vehicle re-equipment is not expected to start before the IM notification, as carriers start the migration process with the prospect of increased operational costs for the dual equipping of vehicles. In fact, older and current surveys show that **the essential motivation of carriers is lacking** (see Chapter 3.3). For a dual terminal scenario, which is more challenging and time-critical for carriers, there must therefore be incentives from the outset to encourage participation in the migration. Such incentives must take the form not only of financial support but also pilot projects to test the installed on-board FRMCS equipment as a condition for timely approval.

- **The availability of the necessary components** on the market will be different for infrastructure and vehicles - Although joint prototyping and testing are part of the standard's preparation, vehicle equipment manufacturers who have not participated in these campaigns may be behind schedule in terms of the required volume of hardware production and the development of software with the necessary features and approvals. The conditions for in-vehicle fitment are far more diverse, the number of participating entities and prototypes requiring approval far higher, and the process significantly longer. The risk of approved solutions being unavailable is therefore higher for carriers than for IM. From this perspective, the **dual terminal scenario,** in which carriers start the migration process is, at least for them, **high risk.**

- Both scenarios allow for a **partial overlap in time for the migration of vehicles and infrastructure**, which can slightly shorten the whole migration process and mitigate the significantly higher operating costs of the replaced GSM-R. However, the proportion of vehicles supporting a given communication method is significantly higher than the proportion of the network on which this communication is used. The ratios shown in Table 8 are obtained from a network model based on random paths of different lengths plotted against each other. Examples of the calculation tables are given in Annex 2 of this study.

- The dual infrastructure scenario strongly depends on the **viability of GSM-R and FRMCS coexistence in the 900MHz band** (see Chapter 2.1.3). **That coexistence has not yet been definitively tested.** Both options limit the bandwidth and thus the transmission capacity of the GSM-R network to a certain extent, and assume a gradual frequency replanning during migration to optimise throughput. This entails **risks of insufficient GSM-R capacity** for the vehicles still using this standard and risks of errors and subsequent operational failures during interventions in the system configuration. From this point of view, the safer option of deploying FRMCS in the 1900MHz band (or in another possible band) demands more modifications of passive infrastructure. That will be necessary given the conditions in the Czech Republic (see Chapter 2.2) and also depends on the timely allocation of spectrum for railway use.

- Another important aspect is the **coexistence of both systems in terms of their antenna placement** on vehicles or infrastructure masts (gNB). There can be spatial problems on both types of platform. Other antenna systems may already occupy part of the space and not allow the necessary separation between the systems, requiring additional elements of selectivity. In the case of infrastructure masts, there are also problems of static load-bearing capacity, especially when large multi-element radiators are subject to wind stress. While the problems of masts can be solved by replacing them, at the cost of increased investment and extended construction time, for vehicles this is very often not an option.

- Possible dates for the start of migration oscillate due to the **uncertain timing for completion of FRMCS standardisation**, at least up to Baseline 1 (V3) and the subsequent commercial availability of components between 2029 and 2032 (the latter

is a pessimistic variant of the ERA recommendation). National pilots, although theoretically already planned to coincide with the pan-European testing of MORANE 2 from 2025 [37], are only realistic in this timeframe, as neither prototypes rebuilt for MORANE 2, let alone mass production of FRMCS components, will be available at the necessary scale in the period before V3. The timelines for technical preparation of network migration will therefore be very tight, with all the associated risks.

- The current standardisation process is under great time pressure, which may result in future FRMCS V3 standards being limited in scope. That implies a risk that subsequent versions of FRMCS will not be **backwards compatible**. Thus, during the migration period (2027 - 2050), the situation that occurred during introduction of ETCS may be repeated, where the forced equipping of Baseline 2 vehicles before 2020 must be upgraded to Baseline 3 by 2030, resulting in a shortened operational life and a shortfall of investment recovery.

Table 8 compares the importance of some of these factors or thresholds for the two main scenarios.

Table 8 - Main differences between theoretical migration scenarios

	Dual infrastructure scenario	**Dual terminal scenario**
Time margins for notification of GSM-R decommissioning according to the CCS TSI	larger	small to none
Availability of FRMCS components on the market	more important for IM	critical for carriers
Vehicle and infrastructure migration overlap (migrated part)	>69% of the network for 20% of vehicles	>66% of vehicles on 20% of the network
Impact of the limits of GSM-R and FRMCS coexistence in the 900MHz band	essential	minimal (without long-term coexistence)
Restrictions on the coexistence of systems in terms of antenna location	risk of replacing gNB masts due to insufficient space and load capacity	often unsolvable space constraints on the roof of the vehicle

In terms of overall **scenario preferences**, there is a clear desire from source [2] and from the discussions held within the working group of this study for **IMs and carriers to shift responsibility for maintaining both technologies during migration to the other side**: while the only clearly articulated preference on the carriers side was a scenario with an overlay of both systems on the infrastructure, 45% of the European IMs interviewed in the survey favoured a migration scenario using dual terminals or a mixed scenario for special conditions. In the Czech Republic, both SŽ and MD prefer the option of a one-off fast migration to FRMCS (i.e. the option with an installation of dual terminals on vehicles). However, the current analysis shows that **the scenario with dual terminals is probably not feasible in the required timeframe:** it is more time-consuming for carriers and the availability of components and the time needed to get vehicle modifications approved are critical risk factors. The main risk for dual infrastructure, on the other hand, is only whether coexistence of both systems in the 900MHz band can be achieved in practice.

3.2 Migration plans of specific entities

Based on the available sources, only **the DB InfraGO migration plan** [1] is specific enough. In the default state, at DB InfraGO, GSM-R is the key safety communication system (ETCS) and the voice communication service solution for vehicles, with a base station range averaging 7.6km, a dispatcher station per 9.2km of track, one vehicle radio terminal (cab radio or EDOR) and 2.5 handheld terminals (HHT) per 1km of track.

The 7 specific steps of the DB InfraGO migration plan assume migration on individual lines and individual applications, which requires parallel operation of GSM-R and FRMCS systems for a certain period **and dual equipment on vehicles** for GSM-R and FRMCS.

- The plan starts with island pilot operations on lines so far equipped with analogue radio (1 location, namely the SRCC test polygon on the border of Saxony and the Czech Republic), where infrastructure, vehicle equipment and operating models will be tested together. It will continue with live operation on regional lines (2 sites) where more carriers will be involved. The processes of planning, construction and operation of FRMCS components will be optimised, as well as operation of the railway in this environment.
- The next steps will be to deploy FRMCS in parallel with GSM-R - first on regional lines (1 site) and later on main lines (2 sites), where FRMCS and GSM-R cooperation and corresponding operational procedures will be tested and optimised. On main lines, the factors of higher density multi-carrier traffic and high speeds will then be added to the testing and optimisation.
- The next steps will be to expand beyond the DB InfraGO network, first through individual border crossings, which have been operated under GSM-R so far. This will add issues of cooperation with foreign railway administrations and MNOs, including

international roaming and operational procedures for FRMCS networks and users. The first deployment of ATO GoA2 is also planned in this step.

- The seventh and final step is the gradual migration of the individual tracks by the procedures fine-tuned in the previous steps.

Parallel operation of the systems (and the costs thereof) are to be reduced as quickly as possible (again on individual lines) and efforts will be made to realise the benefits of FRMCS operation for IM and carriers as soon as possible. The timing of individual activities in the preparation, construction and transition of operations to FRMCS is assumed to be as follows:

- **The development and testing of prototypes** on a dedicated test track (Digitales Testfeld Bahn), under conditions recommended by the manufacturers' laboratories, is already underway, independent of the CCS 2023 TSI scheduled for early 2026.
- **The design, planning, approval, and construction of the core network and pilot lines** follows immediately after the release of the CCS TSI (9/2023) with completion expected at the end of 2028. It includes preparation of the area construction. Pilot operations are foreseen for the period 2027-2028 following release of the FRMCS V3 standards in the 2026 CCS TSI.
- The piloting and construction on the DB InfraGO network is to start with **site preparations** in 2024 – 2025, followed by **implementation of the core network and its services and the equipping of the pilot lines** by the end of 2028. Together with the previous points, they form **Phase 1 of** the DB InfraGO migration plan.
- Following the release of the CCS 2026 TSI (FRMCS V3 standards), the planned widespread deployment of FRMCS also starts and the 5-year period for implementation of FRMCS on the carriers side (vehicles) starts.
- The actual **migration period of** parallel operation of FRMCS and GSM-R will follow successful completion of the pilot operations (planned for 2029 - 2035). Within this period, after preparations on the carriers' side, the gradual **switch-off of the GSM-R network** will start (planned for 2032 - 2035).

The DB InfraGO plan foresees the integration of MNO networks for backup purposes, similar to today's GSM-P communication environment.

A similar arrangement is envisaged in **Norway's migration plan**, developed jointly by the state-owned Directorate of Railways (Jernbanedirektoratet - a ministerial advisory body responsible for long-term planning and coordination of the sector) and the national IM Bane NOR. The cost of implementing this option on the Norwegian network’s 11,000 km of track with 8,000 current GSM-R terminals is estimated at €85m.

Similarly, the **French SNCF Reseau plan** [36] foresees the replacement of GSM-R by 2035

- on at least 97% of its TEN-T network with its own infrastructure in RMR bands, where it expects in particular higher availability of connections for ETCS L2 and for the network of regional lines using FRMCS in MNO bands.
- migration to be implemented in the years 2032 - 2035 by a one-time switch-over of 6 dispatching areas in 2 - 3 steps, (theoretically in a night-time lockout) - i.e. in an **extreme form of a dual terminals scenario**. This implies the re-equipment of a decisive part of the vehicles in a short period of 3 - 6 years.

3.3 Stakeholder motivation

A study [2] in 2015 tried to map the motivations for migration among the main entities involved in railway operations - infrastructure managers (IMs) and carriers. However, the study’s informative power was limited, especially on the side of the carriers, due to the low number of survey respondents.

Motivation of subjects in the **Czech Republic’s railway sector** was mapped in the framework of the present study by a questionnaire with a similar structure. The main difference was that past migration projects were represented by the introduction of ETCS L2 instead of GSM-R, which had a smaller time gap from the study period and was perceived in the preliminary consultations as a more relevant representative example of a migration project. In addition, in contrast to the original study, evaluation of the responses was carried out with a distinction between passenger and freight operators. Their business conditions and financing methods are diametrically opposed in the Czech Republic, and therefore they have fundamentally different views of the economics of any technical change, including the introduction of FRMCS.

The following table summarises and compares the results for the earlier study’s set of respondents (Europe) and for the subjects surveyed in the present study (Czech Republic). Average ratings of the strength of motivation are quantified on a scale from 1 (marginal) to 5 (most important). The values given in parentheses had a large variance or a small number of responses and are therefore not considered representative:

Table 9 - Possible motivations for IMs and carriers to switch to FRMCS

Motivation aspect	Administrators (IM)		Carriers	
	Europe	Czech Republic	Europe	Czech Republic
Degradation of the installed base of equipment's reliability	(2)	3	(2,5)	(1,0)
Increase in maintenance costs	(3)	2	(2,5)	0,5
Prospect of cost reduction	(3)	-	(2,5)	-
Potential for the introduction of new services and applications	3	3	(3)	(2,5)
End of life cycle of key technologies (specifically GSM-R)	4,5	2	(2,5)	2,5
EU regulation	4	4	4,5	5
Follow-up to other projects - construction of new lines, acquisition of vehicles, introduction of ETCS, etc.	4	2	(3)	0,5
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 motivational factors can be evaluated in more detail thusly:

- Even with regular maintenance, **degradation of the reliability of the installed base of equipment** will eventually warrant physical replacement, which creates an opportunity to transition to a successor technology. However, this motivation is perceived as unimportant by IM and carriers alike in Europe, and more strongly by IM than carriers in the Czech Republic.
- The **increase in maintenance costs** coincides with the fear of the end of GSM/GSM-R support. Both can be seen as motivating. In addition to the increasing difficulty of obtaining spare parts, a gradual loss of 2G technology specialists can be expected. However, as incentives, these are moderate or uncertain - and minimal for carriers in the Czech Republic - as even the quoted costs are strikingly small compared to Europe.
- The **expected cost reductions** vary by the type of entity. In Europe: while IMs expect lower **maintenance** costs for the successor technology than for GSM-R, carriers hope for lower **acquisition costs**. Cost reduction on the IM side includes in principle the possibility of railways sharing utilisation of the emerging 4G/5G critical communication networks for emergency responders and security forces (PPDR). In the Czech Republic, this motivation is completely missing on both sides.
- The possibility of supporting and offering **new services and applications** is perceived in Europe and the Czech Republic as a medium-strength motivation, usually in the form of better/faster communication enabling higher operational use of the line, or enabling new applications that will reduce operating costs, or as a chance to develop services and applications that cannot be implemented on GSM-R. However, the only concrete examples given are the transfer of (critical) ATO and (performance) TCMS, diagnostics, etc. from the only possible IM communication today to FRMCS. Other possible benefits are hidden under the vague slogan "digitalization of the railway" [1]. The expected applications are mostly non-critical. The deployment of safety-critical applications is neither motivated by the carriers nor by the customers of the services, but only forced by the legislation and its implementing authorities. For passenger carriers, this includes an interest in providing new broadband services for passengers, but these are beyond the scope of this study. Some of these applications are already being provided via 4G LTE by MNOs and larger carriers of passengers. This motivation is absent for small carriers because the required investments in IT are not cost-effective for them. It is more cost-effective for them to continue with legacy process management without IT support. Moreover, while FRMCS will provide superior communications quality for applications, it will not provide cheaper operation, and using only RMR bands in its early days, it will not even provide sufficient capacity (see Chapter 2.6). The findings of our research on this point are discussed in more detail in Chapter 1.1.
- From the IM perspective, **the end of the life cycle of key technologies (i.e. GSM-R)** will significantly increase operating costs and practically prevent further network development (deployment of additional lines). In terms of time, the end of the GSM-R life cycle determines the expected end of the migration period. This is clearly the **primary motivation for European IMs**, reinforced for some administrations by the expected end of GSM operation by public MNOs that provide roaming in rail-sparse areas or for back-up communications. It is perceived as a weaker motivation in the Czech Republic, especially for IM.
- **EU regulation** was and is seen primarily as a legal obligation to implement the new system. It was the **only motivation rated consistently high** among all those surveyed. In practice, it manifests as **legislative requirements** delegated by IM to carriers, which are threatened with restrictions on the transitivity of their vehicles, accompanied by loss of revenue, a

decrease in the efficiency of operations, or sanctions. A more detailed study [5GBB-D] has already confirmed that under these conditions, it is not possible to quantify the benefits using the usual CBA methods.

- The **follow-up to other plans**, namely the construction of ETCS L2, has for European IMs exposed not only the absence of a suitable radio carrier, but also the insufficiency of the existing GSM-R installation, in terms of capacity and functionality. In this case, upgrading to a successor technology is a valid option. For European carriers, the only prevailing concern now is the need for a guarantee that the radio technology newly installed on their vehicles won't need to be replaced again prematurely. The Czech operators initially reported this element of motivation as weaker than the European average, but the issues of **linking the communication technology to ETCS** and the poor experience changing the installed technology even on newly acquired vehicles proved central to the discussions.
- The motivation for **standardisation and making new products commercially available** is low in Europe and the Czech Republic, and negligible for carriers. At least for carriers in the Czech Republic, this is again due to the bad experience of past technology migrations, such as the transitions from national radio systems to GSM-R or to ETCS security in exclusive operation. In addition to the implementation and financing problems described below, it was the different national approaches and specificities (e.g. caused by the priority deployment of GSM-R in border sections following a more extensive construction in a neighbouring network) that led to not fully interoperable implementations and limitations in vehicle transitivity.

Although the respondents to the survey conducted for this study did not explicitly mention 'other' sources of motivation for switching to FRMCS, in open discussion they cited several recurring factors that **disincentivise carriers in particular** from switching to a new technology. This was confirmed by an earlier joint analysis by DB and SNCF in [1]:

- The **vehicle approval process** is complex and administratively and financially demanding. At the same time it is devalued by pressures to shorten and formalise the verification procedure, the results of which are already not representative of real-world conditions and do not guarantee interoperability. The joint analysis of DB and SNCF in [1] suggested a solution in the **independent readiness of hardware and software for FRMCS**. Where FRMCS-compatible hardware is available, vehicles can be equipped in advance. Only software upgrades would then need to be implemented during the acute phase of migration and the migration period for carriers can be extended. However, putting that into practice depends on software modifications that can be performed on vehicles without having to go through recertification, and that is unrealistic, at least in Czech conditions. A related question is: to what extent will the possible incompleteness of the FRMCS specifications, even in V2 and V3, make early hardware modifications risky?
- The de facto **monopoly power of manufacturers of** railway-specific equipment, and the dependence of the certification procedure on the vehicle manufacturer, can effectively block retrofits, especially for small series of older vehicles in which there is no longer active commercial interest. The integration of new technologies is demanding in the installation phase as well as in vehicle modifications, especially for older vehicles. The slow product innovation cycle (more than 7 years) or even complete cessation of innovation is compounded by the **limited capacity** of design and test facilities and workshops, and is probably insufficient for the high volume of work expected in the 2029-2035 timeframe, with GSM-R going out of service during 2032. Practically all European railways will implement their migrations in the same time-frame, processing about 10,000 vehicles per year. This surge in demand will lead to **prices significantly higher** than for similar commodity technologies and associated servicing, making migration to the new technology uneconomic.
- **Unsecured financing** of the relatively large investments needed, especially on the carrier side, is confirmed by the findings of [1]. According to the experience of carriers in the Czech Republic, **financial support instruments** are supposed to solve this problem, but they do not motivate carriers because the actual level of support is insufficient. One reason is the constant changing of requirements and regulations, leaving the customer unable to specify appropriate equipment and delaying the finalization of product offers. This leads to the splitting of deliveries into phases, with the later ones no longer eligible for financial support. That in turn reduces the actual share of cost support from the claimed 80% to, for example, 50%. The share of aid is crucial to the economic viability of the project, because realistic financing methods force carriers to reflect forced costs in the price of their services. This reduces their ability to compete. In the case of freight transport, the result is often a switch of customers to road transport. In the case of passenger transport, contracts can be lost with public transport service providers.

The current 2023 CCS TSIs establish a **forced transition to System Version 3.0 (Baseline 4).** This was introduced as the basis for a new generation of FRMCS-compliant equipment. Yet commercial availability of the equipment is not expected before 2032, by which time the number of vehicles in service or delivered with support for older versions (by 2032, mostly Baseline 3) will grow. The number of vehicles requiring upgrades may by then not be manageable. Therefore, alternatives to the CCS 2023 TSI with significantly less required recertification would be much more acceptable, especially for hauliers. Specifically, a solution with an additional function block added to the existing ETCS Baseline 3 (the so-called **FRMCS adapter**) or a so-called **light version** that implements the Coordinating function and FRMCS Communication Function according to the CCS 2023 TSI but does not change the security functions and the actual ETCS application remains Baseline 3 (System Version 2.1). Baseline 4 changes the Safety Function.

3.4 Specific migration process in the Czech Republic

Like the rail traffic support applications described in Chapter 1.1, the Czech Ministry of Transport‘s strategic document titled *National ERTMS Implementation Plan* [26] does not contain any detailed plans or timeframe for the transition to FRMCS. However, a working document of the Railway Administration s.o., covering the period from 2020 to 2040, was made available within the working group for the preparation of this study. It assumes a 10-year period of simultaneous migrations of infrastructure and vehicles. According to the results of [25] and discussions in the working group, the input conditions on the Czech Republic’s main lines can be characterised as follows:

- Migration implemented only in the 900MHz band (see Chapter 2.1.3) is generally considered technically feasible, although the analysis of communication requirements does not provide a longer-term perspective. For this option, the same coverage as the existing GSM-R system is assumed, with an average gNB inter-site distance of 3.9km within the network (per SŽ data provided in the survey) or up to 5.8km in flat sections of main lines, according to [25] part C.
- Due to parallel coverage of the lines by MNO signals for commercial applications, for which the 800MHz (n20) and 1800MHz (n3) bands are used, the passive infrastructure (masts, power connections, IP transmission and communication environment) is partly ready for possible deployment of FRMCS in the 1900MHz band, provided that the infrastructure is shared between IM and MNO. Critical to this are the mast loading and spatial conditions: to ensure that the new antenna systems are mounted at the required height within the windward area margin (random mast loading) and the antennas are spatially separated for the necessary shielding effect (at least 2m vertically for the RMR bands) [24] [6]. It is likely that not all masts will meet these conditions. [25] assumes height increases would be needed at about 1/3 of the existing mast sites, which effectively means mast replacement.
- An important deficiency of the existing passive infrastructure is the exhausted capacity of the SŽ fibre optic cable network, which will require renewal. Those costs were not foreseen in the cited models and must be included in the costs of passive infrastructure modifications under the heading of fibre optic connections with a spur from the DOC at distances of hundreds of metres.
- Compared to other countries, there is a much stronger link in the Czech Republic between the planned FRMCS migration and the already ongoing migration between different ETCS Baselines. The **historical experience of carriers with technology migration projects is poor.** An example of unmanaged long-term (in fact permanent) migration is the introduction of ETCS to replace the national signalling system LS. The motivation in this case was clearly only the IM requirement, without any tangible benefits for the carriers. The ambitious plan, implemented up to 10 years ahead of other countries, was accompanied by constant changes in the rules and requirements for Baseline ETCS during implementation, and the unavailability of target technologies/products and services on the market. While initially only the commercially available Baseline 2 could be deployed, after 2021 there was a push to upgrade all vehicles to Baseline 3. Smaller carriers especially, operating older vehicles with small numbers of vehicles in each series, encountered vendor disinterest in such retrofit projects, as well as abusive hangman's deadlines for purchasing and installing the necessary components, user training and other commissioning steps that resulted in huge costs. As a result of an unclear and ultimately unfulfilled financial support policy, these costs remained unrecovered. The actual amount of support ended up being significantly less than expected.

Table 10 compares the various characteristics and cost items of the model’s two theoretical options, with parameters as close as possible to the situation in the Czech Republic as gleaned from the questionnaire survey. The economic model from study [2] was again used for costing, but it had some currently unacceptable simplifications. So details of the model were modified for the purposes of this study to better describe the specific network’s reality:

- The original model assumed that the GSM-R network coverage and migration would be completed at a scale of 1:1, which will not be the case in the Czech Republic. In such a case, the OPEX in the initial steps of migration was stagnant, with investments limited to simple technology renewal in the range of a few percent. The modified model foresees a partial and continuous expansion of the GSM-R network coverage according to the IM’s original development plans, until the start of the FRMCS network construction.
- The original model did not foresee investment in the passive part of the infrastructure, which was assumed to be used unchanged for the emerging FRMCS technology. As a consequence, the scenarios studied were limited to the replacement of GSM-R in the 900MHz band, where the old and new radio technologies‘ coverage do not differ significantly (see Chapter 2.1). In the specific conditions of this study, that assumption is not fulfilled, because one of the studied options is deployment in the 1900MHz band with a different cell structure (smaller ISDs), requiring an extension of the passive infrastructure with additional facilities in the range of tens of percent. Therefore, the model was modified to include passive infrastructure as a separate component with variable levels of investment (CAPEX) and operating costs (OPEX).
- The original model for carriers did not foresee the renewal of GSM-R equipment due to its end of life. The modified model includes renewal in the carrier's operating costs until the start of the project to replace the original on-board equipment with dual and/or FRMCS-enabled equipment. Similarly, it did not index the operating costs of GSM-R vehicle equipment to reflect a progressive increase in GSM-R prices around the end of support. The modified model includes this progression in the carriers' OPEX for the reasons discussed in Chapter 3.3.

- Due to the strong link between the FRMCS and ETCS migration projects mentioned above, the scenario also quantifies the cost of a forced ETCS upgrade, for all scenarios, associated with the installation of FRMCS (at least support of the Coordinating Function and the communication stack according to UNISIG Subset 037-3). Following the experience with production of ETCS components to date, such an upgrade is also included in the dual terminal scenario, in parallel with the infrastructure transition to FRMCS, in which the shortcomings of the early ETCS Baseline 4 production are expected to require further adjustments.
- The data provided by SŽ showed that the infrastructure construction cost estimates in the original study [2] were significantly underestimated for Czech conditions. Therefore, the model uses values derived from the kilometric investment intensity of new GSM-R construction used in the budgets of the SOPES tool - construction part / passive infrastructure 40%, addition of FRMCS on the existing passive infrastructure.
- After the experience of implementing ETCS, the original model's migration period for IM and carriers in the scenarios is extended to a much more realistic 10 years. Therefore, the second phase of migration in all scenarios falls into **the period after the announced end of GSM-R support**, reflected here by a 100% increase in all costs for renewal and maintenance, with the risk that in such a long period the **cost progression could be even greater**.
- The model uses more recent inflation and discount rates for the Czech economy.

Detailed model inputs, including modelled component prices and operating cost items, are provided in Annex 2 of the Czech version of this study. The outputs of such a simple model are only indicative. For a more accurate comparison of the options specified in the next steps of the migration preparation, a complete Cost-Benefit Analysis (CBA) and a more detailed analysis of material risks will be necessary.

Table 10 - Model economic comparison of migration procedures

Migration scenario	A (dual infrastructure)	B (dual terminal)	C (1900MHz overlay)	D (interoperability issues)
Total length of lines equipped with GSM-R at the beginning of the scenario	2269km	2269km	2269km	2269km
Target length of lines with FRMCS installed	2569km	2569km	2569km	2569km
Number of vehicles equipped with a GSM-R (cab radio) call terminal	4370	4370	4370	4370
Number of vehicles equipped with EDOR for ETCS	2190	2190	2190	2190
Proportion of passive infrastructure requiring replacement or additions due to FRMCS deployment	5 %	5 %	61 %	5 %
Completion of the construction and renewal of the GSM-R system on the infrastructure	2050	2039	2050	2039
Building the FRMCS system on infrastructure in the period	2030 - 2040	2040 - 2050	2030 - 2040	2040 - 2050
Project to re-equip vehicles with FRMCS equipment	2040 - 2050	2030 - 2040	2040 - 2050	2030 - 2040
GSM-R operating on infrastructure up to	2050	2040 - 2050	2050	2040 - 2050
IM investment in FRMCS (years x billion CZK/year)	11 x CZK 0.75 billion	11 x CZK 0.94 billion	11 x CZK 0.96 billion	11 x CZK 0.94 billion
Related IM investments in ETCS (years x billion CZK/year)	11 x CZK 0.69 billion	11 x CZK 0.84 billion	11 x CZK 0.69 billion	11 x CZK 0.84 billion
Carriers' investment in FRMCS (years x billion CZK/year)	11 x CZK 0.27 billion	11 x CZK 0.22 billion	11 x CZK 0.27 billion	21 x CZK 0.26 billion
Related investments of carriers in ETCS (years x billion CZK/year)	11 x CZK 3.0 billion	11 x CZK 2.5 billion	11 x CZK 3.0 billion	11 x CZK 2.5 billion
IM operating costs 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 cost at current prices (NPV) for the period 2025 - 2050 (IM and carriers)	CZK 51 billion	CZK 43 billion	CZK 52 billion	CZK 47 billion

All the quantified options assume migration will be carried out in the 2030 – 2050 period, which is chosen so that, according to current assumptions, the components needed for migration are already on the market. The period is also long enough for the migration to be carried out by carriers and on infrastructure without time overlap. Parameters such as vehicle equipment, life expectancy and component prices are the same for all options. The total costs at current prices (NPV) are quantified for the period 2025-2050, beyond which the options do not differ materially. The CAPEX and OPEX figures are quantified at current prices, applying a constant inflation rate over the whole period under consideration. In addition, a discount rate, also constant over the whole period, is incorporated in the NPV values.

- **Option A** represents a **dual infrastructure migration** scenario. Two immediately consecutive 11-year intervals are planned for the installation of the technology in the infrastructure (step 1) and for outfitting the vehicles (step 3). IM investments in GSM-R technologies are completed in 2029, but operations burdened by increasing costs, including the necessary renewal of full coverage, continue until 2050. The newly built network is used only for testing purposes and operated at minimal cost

until completion. The renewal of GSM-R technology by carriers ends in 2039, when its total cost also peaks at half the level of the subsequent investment in FRMCS, then falls only to the level of routine maintenance, and gradually disappears as the technology on vehicles declines. In terms of NPV, **this option is more expensive compared to the dual terminal option**, the difference being mainly the maintenance and renewal costs of GSM-R on the IM side.

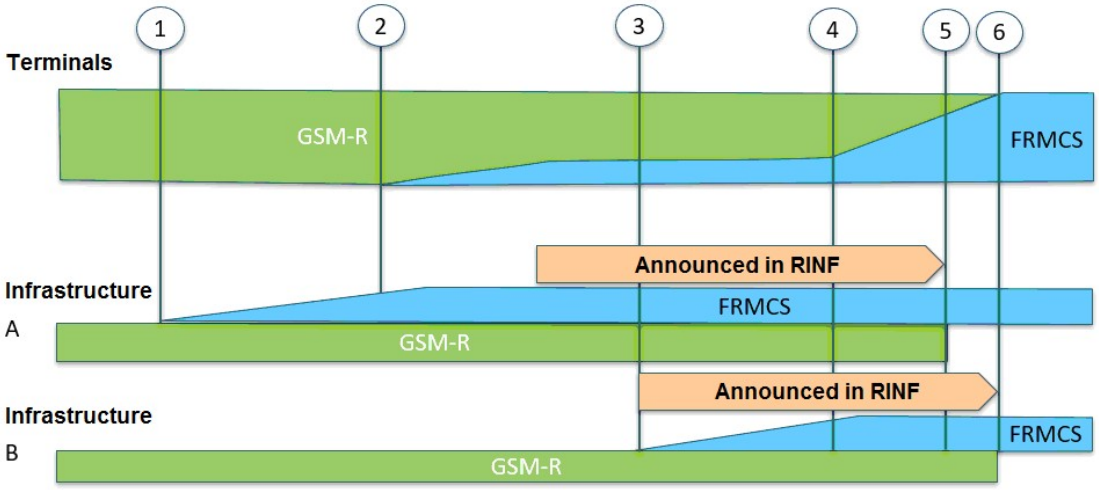
- **Option B** represents a scenario **using dual terminals**. Again, two immediately consecutive 11-year intervals are planned for the equipment of the vehicles (step 1) and for the installation of the technology in the infrastructure (step 3). Although IM's investment in the development of GSM-R technology ends in 2029, operations continue until 2050. But after 2039 operating costs decrease due to the cessation of GSM-R renewal and subsequent decommissioning in sections where FRMCS has replaced GSM-R. The renewal of GSM-R technology by carriers ends immediately in 2029, and its remaining operating costs decrease from 2036 until its retirement in 2040. The investment intensity is higher for IM compared to the previous option, but significantly lower for carriers (with the assumption of financial support for them indicating a need for public funding). The total NPV costs for IM and carriers are also minimal for this option. As with all options**, the decisive cost item is the investment by carriers in the induced ETCS modifications**, with the second highest being the **IM costs associated with maintaining GSM-R operation.**
- **Option C** represents **the construction of FRMCS in the 1900MHz band** with the creation of **dual infrastructure**, where the GSM-R network is operated in the 900MHz band without change. The 1900MHz deployment, in addition to the replacement of some parts of the passive infrastructure, involves an increase of 56% in the number of gNBs (the maximum value, determined by analysing the results of the study [25] (see Chapter 2.2.1). That does not have to be accomplished in the early stages of operation (see Chapter 2.6) to achieve the necessary reduction in ISD. Other costs for vehicle and infrastructure equipment are considered the same as for Option A in the 900MHz band, due to the lack of more accurate data. The model result then confirms that this **change in passive infrastructure** is the main difference - an increase of about 2 billion CZK in IM investment in the overall NPV of the migration, due to the high discounting of 1 billion CZK.
- **Option D** is again a scenario **using dual terminals,** but this time assuming the implementation specifications are not fixed, versions are not fully interoperable with the infrastructure, or the current Baseline ETCS are not available for implementation on vehicles. From the IM perspective, this option is the same as option A. The associated investment by carriers in ETCS modifications is the same. However, the deployment of not fully interoperable versions of on-board FRMCS equipment will require, according to the experience with ETCS, continued investment in on-board parts for the entire migration period of 21 years, representing **an increase of CZK 2.5 billion for carriers**. In spite of this increase, however, even Option D is more advantageous in terms of overall NPV than the more feasible dual infrastructure scenario (see Chapter 3.1).

The result of the model confirms the carriers' view that **stability of the specifications** and **full interoperability of FRMCS components with each other and especially with ETCS** are crucial to keeping migration costs within reasonable limits. A scenario involving modifications to ETCS installations would be far more unfavourable than the one quantified, due to the ratio of FRMCS and ETCS costs.

3.5 Timing of the transition from GSM-R

The study [2] also included scenarios involving multiple neighbouring countries with different timing of migration to FRMCS. The variations are again based on the basic division into a procedure with overlapping systems on the infrastructure and using dual terminals as described in Chapter 3.1. The migration procedure with **dual infrastructure in two interconnected networks (**differing from the cited study, IM A denotes the network starting the migration, IM B the delayed network) includes the following steps, regardless of the networks‘ size:

Figure 4 - Migration scenario of two networks with dual infrastructure



1: Initial stage - The infrastructure and carriers of both networks use GSM-R operationally. IM A is building the FRMCS system in advance, while the carriers are in the process of commercial and technical preparation for migration (selecting suppliers, testing and type-approval of prototypes using fragments of FRMCS infrastructure built by IM A, etc.).

2: IM A launches FRMCS on a significant part of its infrastructure. Carriers start the serial retrofit of their vehicles (and other communication terminals) to FRMCS, but only the part using infrastructure A, because the upgraded vehicles no longer support GSM-R and thus lose transitivity to infrastructure B. Carriers are therefore waiting for a significant part of the fleet to start migrating to network B. However, the GSM-R infrastructure of network A also remains in operation due to vehicles migrating to/from network B, but at IM A's expense. This OPEX is gradually increasing as GSM-R support ends. At some point in this step, IM A announces the date of termination of GSM-R operation according to CCS TSI Annex I §7.3.1.2.

3: IM B builds the FRMCS and at the latest in this step announces the date of termination of GSM-R operation.

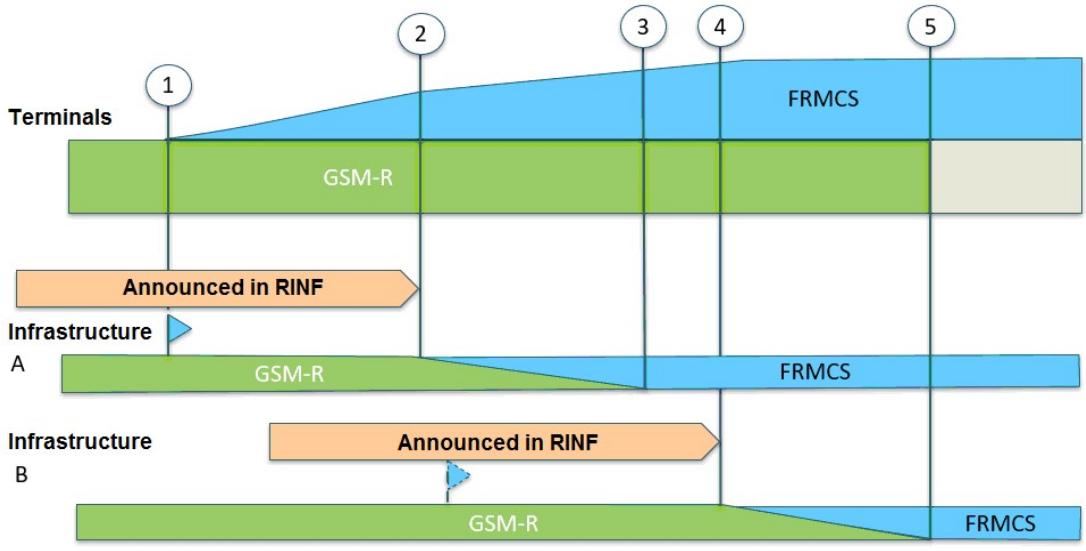
4: IM A launches FRMCS on a significant part of its infrastructure and the carriers can continue to upgrade the remaining vehicles to FRMCS, which used only B's infrastructure.

5: Vehicles of network B entering infrastructure B are upgraded and IM A may cease GSM-R operation.

6: Vehicle migrations are also terminated on network B and its IM may therefore terminate GSM-R operation.

In contrast, the steps of the procedure using **dual terminals** are as follows:

Figure 5 - Migration scenario of two networks with dual terminals



1: Initial stage - Infrastructure and carriers use GSM-R operationally. IM A had to announce well in advance the first GSM-R end-of-life dates falling under Step 2 according to CCS TSI Annex I §7.3.1.2. Carriers retrofit all vehicles using IM A with FRMCS-enabled terminals, or upgrade in advance to terminals supporting both technologies. During this step, the retrofitted vehicles are tested and type-approved, for which the IM provides the pilot track section.

2: Start of FRMCS construction - Vehicles using Infrastructure A are significantly equipped to operate the FRMCS while IM A is building and gradually commissioning the FRMCS. Carriers continue to re-equip vehicles, but also continue to use the GSM-R infrastructure on the B network. GSM-R OPEX is increasing as support ends. Even IM B needs to announce well in advance the first GSM-R end-of-life dates falling under Step 4 and, where appropriate, provide pilot infrastructure for testing and approving vehicle equipment.

3: IM A ceases GSM-R operation on the whole network and carriers use FRMCS, with which their vehicles are already equipped. On infrastructure B, GSM-R continues to operate and its OPEX continues to increase.

4: Carriers are finalising the fitment of FRMCS-enabled terminals on vehicles using only Infrastructure B, and IM B is gradually building toward the FRMCS launch.

5: IM B completed the construction and commissioning of FRMCS and ceased GSM-R operations throughout the network. The fitting of GSM-R vehicles is no longer necessary and the renewal and maintenance of the GSM-R vehicles can be terminated.

In addition to the conditions and risks discussed in Chapter 3.1, there are additional risks associated with cross-border traffic:

- **Changes to specifications** during the migration period, which are very likely, given the current standardisation process, carry the risk that implementations in neighbouring networks will not be fully interoperable, even temporarily. Migration to Network A specifications will not guarantee transition to Network B. The current situation where vehicles are equipped with nationally specific subsystems or functions, or upgraded in parallel with the installation of FRMCS on both infrastructures, may then be repeated. Both of these procedures will make the migration of vehicles more expensive and complicated to approve.
- Elements of **national specificity** may be hidden in the common standards themselves. A current example is the content of FRMCS profiles (equivalent to GSM-R SIM), which are planned separately on the vehicle for each network traversed and must be provided by its IM. The unclear situation around changes and approvals of profiles can severely limit vehicle transitivity, at least in the early stages of migration.
- The migration process in the later-migrated network **retroactively affects the process** in the earlier-migrated network. For example, in a dual infrastructure scenario, delaying migration in infrastructure B stops the migration of carrier terminals in network A and consequently prolongs the forced GSM-R operation on infrastructure A. Unilateral termination of GSM-R support on infrastructure A, on the other hand, has an impact on network B carriers, representing an increase in migration costs or a reduction in their transitivity to network A. To limit such effects, **coordination between IMs** is needed, for which **there are not yet adequate tools**.
- The risk of inadequate international coordination is also that different IMs will choose **different types of migration**. The dual terminal approach is safer in this respect. The conditions for carriers are essentially the same, regardless of which scenario IM B chooses. On the other hand, the combination of the scenario with dual infrastructure in network A and the assumption of dual terminals in network B is critical. In this case, network A carriers can only re-equip vehicles for their own network and have to equip others with dual-system terminals, even though their network does not require it. The increased operating costs of IM A for dual system operation are thus partly negated.
- A common but extreme case of both of the above-mentioned uncoordinated procedures are **countries that do not plan to migrate to FRMCS**, e.g. European countries outside the EU. Carriers that want to operate in those countries‘ networks will have to extend indefinitely their support of GSM-R, or even national type B systems on their vehicles, and, despite the technical problems discussed in Chapter 2.1.3 and the procedure of their own IMs, go the way of multistandard terminals.

Table 11 summarises the magnitude of these risks for the two main cross-border scenarios.

Table 11 - Importance of different risks for cross-border traffic scenarios

	Dual infrastructure scenario (on network A)	**Dual terminal scenario**
Changes in standards during the migration period	They make migration more expensive or delay migration for carriers	Making migration more expensive for carriers
Impact of migration rate in network B	More sensitive, delays progress for IM and Network A carriers	Safer, only increases OPEX of carriers
Consequences of different types of migration in both networks	Multi-cost and delay risk for Network A carriers	Safer, does not depend on the IM B option

The dual-terminal scenario, although more financially demanding, especially for carriers, is in many ways less demanding in terms of coordination between the actors involved. It gives essentially the same conditions for network A carriers regardless of which scenario IM B chooses, or in what time-frame. This difference in coordination requirements between the two baseline

scenarios was generally confirmed by the original study [2]. In realistic migration procedures, a certain proportion of dual- terminal vehicle use will be highly likely.

3.5.1 Results of the models

The main result of the simulations carried out in study [2] is **quantification of the expected costs at current prices (NPV) for all the studied options**. For modelling purposes, the studied rail networks were divided into three size categories. Despite the time lag and some simplifying initial assumptions (shares of cross-border traffic, equal price level for all participants, length of migration periods, etc.), in addition to the conclusions presented in the cited study, further conclusions can be drawn from the quantified NPVs regarding the impact of the timing of migration on the FRMCS in different neighbouring networks on the costs borne by the IMs and carriers involved:

- In the case of migration of a medium network delayed behind the migration of a neighbouring large network (the quantified case corresponds well to the case of Germany and the Czech Republic), the impact on the larger initiating network was indifferent (up to ±5%) and **the cost increase is entirely borne by the smaller delayed network** (IM by >10%, more pronounced for dual terminal migration).
- In all cases, the percentages must be adjusted for the overall increase in migration costs in two interconnected networks compared to two isolated migrations, which is 3-15% depending on the specific variant. However, the ratio of IM migration costs to carriers is several times higher (5:1 to 10:1 depending on the variant), so the increase is usually entirely attributable to IM.

In order to refine the results to the actual conditions of the Czech network, the model mentioned in Chapter 3.4 was used in a mode including cross-border traffic to the network with a different migration timetable. As well as modelling the situation in the isolated network, the model was updated in several ways:

- The original model assumed that the proportion of upgraded vehicles when FRMCS is implemented on vehicles and infrastructure simultaneously is the same as the proportion of upgraded infrastructure. More detailed network traffic models show that this assumption is wrong and the proportion of vehicles communicating in a particular standard is always higher than the proportion of that standard in the infrastructure. Specific examples of the differences have already been given in Chapter 3.1.
- The original cross-border traffic model quantified the expected costs of both networks under the simplifying assumption of the same price level in both countries. The research carried out as part of this study shows that this assumption is not correct. As more specific data from other networks could not be obtained within the timeframe for the study, the model has been simplified to quantify the costs of only one network, which is the Czech network. A consequence of the simplification is that the model results do not depend on the size of the foreign network, so the discussion of variants with different ratios of network sizes, which is quite extensive in reference [2], is irrelevant here.

The modelling therefore focused on the economic evaluation of the selected risks from Chapter 3.5 The results are presented in the following table in the same structure as the results for the isolated network in Chapter 3.4:

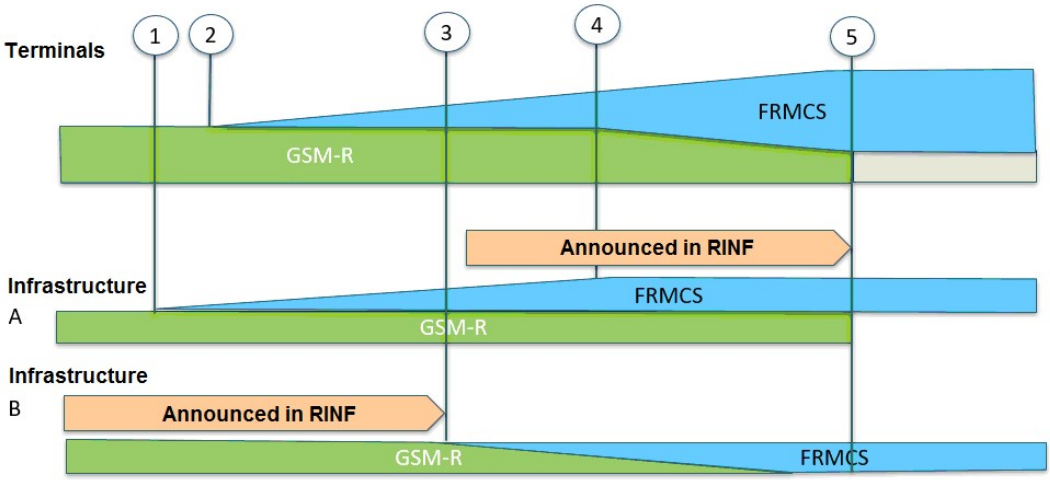
Table 12 - Model economic comparison of selected migration procedures for two neighbouring networks

Migration scenario	Option E (early migration)	Option F (later migration)	Option G (various migrations)
For the total length of domestic lines equipped with GSM-R, FRMCS installation, number of vehicles and the proportion of passive infrastructure renewal, see Table 10 in chap.3.4			
Completion of the construction and renewal of the GSM-R system on its own infrastructure	2050	2050	2050
Building the FRMCS system on its own infrastructure in the period	2030 - 2040	2032 - 2042	2030 - 2040
Project to re-equip vehicles with FRMCS equipment	2040 - 2050	2042 - 2050	2037 - 2047
Operation of GSM-R on own infrastructure up to	2050	2050	2050
Construction of FRMCS in a neighbouring network	2041 - 2046	2030 - 2035	2041 - 2048
Termination of GSM-R operation in a neighbouring network	after 2050	2045	2041 - 2048

Migration scenario	Option E (early migration)	Option F (later migration)	Option G (various migrations)
IM investment in FRMCS (years x billion CZK/year)	11 x CZK 0.77 billion	11 x CZK 0.8 billion	11 x CZK 0.77 billion
Related IM investments in ETCS (years x billion CZK/year)	11 x CZK 0.69 billion	11 x CZK 0.72 billion	11 x CZK 0.69 billion
Carriers' investment in FRMCS (years x billion CZK/year)	9 x CZK 0.32 billion	9 x CZK 0.35 billion	11 x CZK 0.25 billion
Related investments of carriers in ETCS (years x billion CZK/year)	9 x CZK 3.7 billion	9 x CZK 3.9 billion	11 x CZK 2.9 billion
IM operating costs included in the model for the period under review	CZK 24 billion	CZK 24 billion	CZK 24 billion
Total cost at current prices (NPV) for the period 2025 - 2040 (IM and carriers)	50 billion CZK	CZK 51 billion	CZK 51 billion

- **Option E** models the more likely approach expected from the discussions: the **migration of the Czech infrastructure will start earlier than in neighbouring countries**. Among the reasons for this is the limitation of subsequently unused investments in the GSM-R system whose planned completion overlaps with the expected migration period. This variant is constructed on top of a type of dual infrastructure scenario, which has been shown by previous analyses to be more realistic and also more sensitive to various external influences. The FRMCS infrastructure on the B network does not become operational until 2046 in this scenario, so that domestic carriers can only upgrade about 40% of their fleet (unless they equip them with dual terminals) for the sake of transition to the B network, so that the necessary proportion of vehicles transitioning to the B infrastructure still remains as of 2046. This is modelled by a break in investment by the carriers in 2045-46, followed by an accelerated migration so that the re-equipment occurs by 2050, when GSM-R is discontinued on both networks. From an IM perspective, this option is cost equivalent to Option A in Chapter 3.4. The option's results also cover the risk of slowing down the migration process in neighbouring networks, as even in this case the commissioning of a significant part of the FRMCS infrastructure on Network B is crucial.
- **Option F** models the opposite procedure under the same conditions - the **Czech infrastructure will be migrated later than the infrastructure of neighbouring networks**. While the construction and commissioning of the FRMCS infrastructure in its own network will be delayed by 2 years after Option A from Chapter 3.4, full coverage of the neighbouring network will be ready from 2035 and GSM-R operation on it will be terminated as early as 2045. Carriers will have to wait to install FRMCS on the home network for the sake of transitivity, and will have to quickly re-equip once it is fully operational, so as not to limit the transitivity of some vehicles travelling on the neighbouring network. The further progression of the re-equipment of vehicles is slower, but the overall shortening and delay of migration for carriers with intensive investments, especially in the first years, will lead to increased costs and other material risks. The result for IM is more or less the same as for the baseline. Here, too, the delay in migration will lead to higher costs due to inflation.
- **Option G** again models the impact of a situation where IMs of neighbouring networks choose **the opposite approach** for later migration - **migration with dual terminals** - compared to Option E. The situation is illustrated in Figure 6. Thus, the carriers of their own network have to install dual terminals in advance (at point 2 in Figure 6) on vehicles travelling to the foreign network, which leads to an increased investment at the beginning of the migration step. The installation of FRMCS-only terminals (at point 4 in Figure 6) can only take place on vehicles operating only on their own network, and only after their own FRMCS infrastructure is fully operational. On the other hand, carriers of a foreign network can use GSM-R, which remains in operation even after full migration to FRMCS (4). While there are no cost implications for the domestic IM, accelerated investment by carriers at the beginning of the migration step may lead to overall cost overruns and other material risks. Equipping different vehicles with different types of terminals is likely to be reflected in carriers' OPEX (here modeled by a 50% increase in maintenance costs for lack of more accurate data).

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



The assessment shows that significant differences in the timing and mode of migration in neighbouring countries are not desirable. **The process and timing of migration** for the carriers is dictated by the IM network, which will migrate second (last). Differences in timing result in a **reduction in the migration time available to the carrier** with an accumulation of costs at the start of the migration. For a smaller network performing the migration late, there is a **risk that the IM of a larger neighbouring network will be unwilling to coordinate** the termination of GSM-R operations, thus significantly limiting the transitivity of vehicles to its network. An IM opting for an early dual infrastructure approach, without coordination with neighbouring networks, runs the risk to its carriers of having **to install dual terminals** for transitivity to the neighbouring network and the increased costs on both sides will be partially negated.

4 Legislative and organisational conditions

In Chapter 3.3, the barriers and disincentives expected in the future implementation of the FRMCS were discussed. These are partly due to the existing legal framework. This consists of

- Technical specifications for interoperability - in this particular case, the CCS TSI represented by EC Regulation 2023/1695;
- Rules for the approval (authorisation) procedure for railway vehicles, represented by EC Regulation 2018/545 as amended; and
- The specific conditions of public aid programmes, such as "Ensuring Interoperability in Rail Transport in the Period 2023-2028".

In relation to these and related regulations, Czech representatives to the EC bodies and standardisation institutions forming the European railway legislation should advocate at the international level

- A more flexible structure of **legislation that does not directly impose controversial and substantive obligations.** An example of such an initiative is the ERA's plan to change the status of TSIs, whose extensive mandatory technical annexes are to be replaced by harmonised technical standards to which the TSI Regulation will only refer;
- **Technical standards minimising the interconnection and functional dependency of ERTMS components on each other.** An example is the proposal by DB and SNCF [1] to split the specification and hardware and software for FRMCS, allowing compatible hardware to be fitted to vehicles in advance and the final FRMCS specification to implement only software upgrades);
- **Maximum backward compatibility** when incorporating technical innovations that affect individual components. That would limit the impact of component-level changes on related components. Examples are more acceptable alternatives to TSI CCS 2023, with significantly less scope for recertification; a solution with an additional function block to the existing ETCS Baseline 3 (the so-called FRMCS **adapter**); or a so-called **light version** that implements the Coordinating Function and FRMCS Communication Function according to the CCS 2023 TSI but that does not change the Security Functions. The actual ETCS application remains Baseline 3 (System Version 2.1);
- **Relaxation of the approval procedures for railway vehicles.** The subject of approval should not, in justified cases, be the vehicle as a whole, but only individual components. (An example again being the separately specified hardware and software components as proposed by DB and SNCF [1]). That way, the approval of a component in a vehicle and, in particular, the assessments drawn up by notified/designated bodies, are transferable to its integration into vehicles of similar design and purpose;

...and at the national level, **relaxing the conditions for financial support** in the rail sector so that

- Not only the installation of the listed components, but their upgrading (including software renewal) are accepted as eligible expenditures in financial aid programmes, if the reason is a change in technical regulations. This subsequent support should be a legal entitlement if it was granted for the component in question when it was installed. (Such a modification would address the failure of public support when ongoing changes in the requirements and regulations are not sufficiently reflected in the commercial availability of products and the project fails to meet the final objective within a given timeframe).
- The conditions are relaxed for the project's period of sustainability, and the restrictions on transfers of ownership associated with that period – especially allowing this period to end if there is a significant change in the technical regulations with which the project is supposed to ensure compliance.

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