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Scenarios for Rail and Road communication system coexistence

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EXECUTIVE SUMMARY

The main objective of this document is the identification and definition of coexistence scenarios between road and rail.

For this purpose, the coexistence scenarios are first described from the infrastructure point of view. Then a specific description is devoted to autonomous vehicles. Then the document proposes a description and characterisation of communication applications and services specific for each domain (rail vs. road). These three initial sections set the contextual background for operative scenarios and system coexistence.

Following these background sections, a methodology to define coexistence scenarios from the point of view of telecommunication infrastructure is provided. Based on this methodology, a set of scenarios is defined. The choice of the coexistence scenarios, from the communication point of view, to be analysed from a key performance indicators perspective is out of the scope of the deliverable and will be treated in T6.2.

ABBREVIATIONS AND ACRONYMS

Abbreviation	Description
ATC	Automatic Train Control
ATO	Automatic Train Operation
CAM	Cooperative Awareness Message
CCTV	Closed Circuit TV
CEPT	Conférence Européenne des administrations des Postes et Télécommunications
CKPI	Core Key Performance Indicator
CPM	Collective Perception Message
DENM	Decentralized Environmental Notification Message
ECC	Electronic Communications Committee
EU	European Union
FRMCS	Future Railway Mobile Communication System
GA	Grant Agreement
H2020	Horizon 2020 framework programme
KPI	Key Performance Indicator
MCM	Manoeuvre Coordination Message
MCPTT	Mission Critical Push-To-Talk
PCM	Platooning Control Message
REC	Railway Emergency Call
SKPI	Service Key Performance Indicator
SMF	Session Management Function
TCMS	Train Control Management System
TSI	Technical Specification for Interoperability
UIC	Union International de Chemins de Fer
UPF	User Plane Function
V2I	Vehicle to Roadside Unit or Vehicle to Base Station
VAM	VRU Awareness Message

DEFINITIONS

Term	Term Definition
Application	Provides a solution for a specific communication need that is necessary for railway operations. In the context of this document, an application is interfacing with the FRMCS on-board system, through the OB_{APP} reference point, to receive and transmit information to ground systems (for example, ETCS, DSD, CCTV, passenger announcements, etc.).
Service (3GPP TS 21.905, V17.0.0)	A component of the portfolio of choices offered by service providers to a user, a functionality offered to a user.
Communication services	Communication services enable two-way communication between two or more authorised service users (i.e., applications) from applications towards other applications/entities reachable through various networks (UIC- TOBA-7510: FRMCS Telecom On-Board System-Functional Requirements Specification)
Voice Communication for operational purposes	Voice for user to user or multiuser communication; Voice follows the typical conversational pattern and requires low delay inside the transport system (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)
Critical Video Communication for observation purposes	Critical Video with indirect impact on train operation, e.g. passenger surveillance (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)
Very Critical Video Communication with direct impact on train safety	Very Critical Video with direct impact on safety- related critical train control and operation, e.g. used in driverless (e.g. GoA3/GoA4) operation for automated detection of objects (no human in the loop) or video-based remote control (human in the loop) (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)
Standard Data Communication	Non-Critical data used for the exchange of railway system or communication relevant information; requires high reliable transmission and preservation of the response pattern (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)
Critical Data Communication	Critical data follows the response pattern and requires high reliable transport. This category comprises future and legacy applications e.g. ETCS (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)
Very Critical Data Communication	Very critical data for future rail applications (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)
Messaging	Messaging for the exchange of non-critical short information messages, recorded voice (for example voicemail), data, pictures, video; requires reliable transmission (3GPP TS 22.889 V17.3.0 : §12.10 Use Case: QoS in a railway environment)

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1 INTRODUCTION

The Future Railway Mobile Communication System (FRMCS) [1] is under development by the rail sector. This system will be based on multi radio access technologies (Wi-Fi, LTE, 5G and satellite) to ensure flexibility and availability. In parallel, the automotive industry is working on technical solutions for connected vehicles. ITS-G5 system [2] has been standardized for several years, and solutions to allow hybridization with cellular systems such as LTE-V2X or C-V2X (Cellular Vehicle-to-everything) and future 5G NR technology are under development.

5G NR cellular technology promises significant improvements in terms of latency, throughput and reliability. It will allow the development of ever more robust applications for automatic train, control-command, maintenance, remote control of trains, etc. Thus, 5G paves the way for the digitalization of rail networks of the future that are more connected, more automated and thus more available, safer and more respectful of the environment.

In a necessary context of resources and energy saving, it is crucial to analyse the possibility of coexistence and synergies between Road and Rail communication systems. Indeed, the scope of WP6 is the evaluation of the coexistence of rail and road automotive communication use cases. This work package will evaluate the possible synergies allowed by the FRMCS between both vertical industries based on a situation implying common use cases.

The main objective of D6.1 is the identification and definition of possible rail and road coexistence scenarios. The document is organized as follows. In Section 2, the coexistence scenarios from an infrastructure point of view are proposed. After a general definition of the types of railway lines and roads, the deliverable considers the three main cases: tracks parallel to road, tracks crossing road and the case of tunnels and bridges. In the case related to tracks crossing roads, the level crossing and the tramways cases are differentiated. Section 3 highlights the important case of automated and connected vehicles. Section 4 describes in detail the specific communication services in road and rail domains. Regarding the railway specific communication applications, the deliverable details in particular the FRMCS for train operation, the virtual coupling, the case of urban rail and the Train Control and Monitoring System (TCMS). Examples of Key Performance Indicators extracted from 3GPP documents are proposed. Section 5 focuses on the coexistence question from a telecommunication point of view. Literature analysis regarding existing studies on this specific topic is proposed. Finally, in Section 6, a rigorous methodology for the definition and description of the coexistence scenarios is proposed. Using this methodology, section 7 presents five examples of typical coexistence scenarios.

Based on these scenarios, the next step in Task 6.2 will be to identify the most relevant coexistence scenarios between road and rail domains.

2 COEXISTENCE FROM AN INFRASTRUCTURE POINT OF VIEW

2.1 General definition of types of railway lines and roads

This section aims at defining the different types of railway lines and roads from an infrastructure perspective and main characteristics in terms of speed, numbers of vehicles, number of users, etc.

In railways, it can be found some different types of lines, according to some criteria [3], [4], such as the train maximal speed, the type of environment (urban/sub-urban, regional, *etc*.), distance between adjacent train stations, capacity, total travel time and train composition, among others. The following descriptions are given is just as examples, the different characteristics of the railway lines (depending on the market segment) can change from a country to another.

Normally, the railway lines can be subdivided into:

- **High-Speed Lines (HSL)**:
  - $V_{MAX} \geq 200$ km/h, according to the Technical Specification for Interoperability (TSI) (EC, 1996; UIC, 2014a),
  - Interurban lines operated on zero level crossings,
  - Largest distance, $d_{MIN} \geq 50$ km, between adjacent train stations (i.e. few intermediate stops),
  - Capacity: 16-20 trains/h,
  - Total travel time: 15 - 25 min per Origin to Destination (O-D) pair,
  - Train composition: 8 cars at least (2 locos and 6 coaches);
- **Conventional/Main Lines**:
  - $V_{MAX} < 200$ km/h,
  - National and international interconnection between different cities/regions,
  - Larger distance between adjacent train stations when compared to Suburban/Urban Lines but less than the HSLs,
  - Capacity: at least a double track and often contain multiple parallel tracks,
  - Total travel time: 7 - 20 min per O-D pair,
  - Train composition: 8 cars at least (2 locos and 6 coaches);
- **Regional Lines**:
  - Higher travel speeds as compared to the Rail Rapid Transit (RRT) and Light Rail Transit (LRT),
  - Operate along the rail lines/routes spreading between urban and suburban areas,
  - Lower service frequency and rarer stops at stations on the longer lines/routes,
  - 140-1,800 spaces for passengers,
  - Total travel time: 8 - 20 min per O-D pair,
  - Train composition: 6 cars at least (2 locos and 4 coaches);
- **Urban/Suburban Lines / Tramways**:
  - Low to intermediate speed: varying around 50-80 km/h,
  - Prominent in the major cities and high-density areas,
  - Least distance between adjacent train stations,

- 2-5 minutes between trains at peak times,
- Total travel time: 1-6 min per O-D pair,
- Train composition: 4 cars at least (2 locos and 2 coaches).

Regarding the roadways, distinct types of roads could be defined, according to some criteria [5], [6], such as the speed of travel, traffic flow, distances between adjacent entrances/exits, types of roadside users, road function (flow, area distribution and access), number of lanes and lane width, among others. The examples below are not exhaustive description by they allow to differentiate between type of roads.

The roads can be subdivided into the following three main types:

- **Highways/Motorways:**
  - The general speed limit for motorways in EU Member States is mostly 120 or 130 km/h (Germany does not have a general speed limit for motorways, but a recommended speed of 130 km/h),
  - Less traffic flow,
  - Higher distance between adjacent entrances/exits,
  - Serve exclusively motorised traffic,
  - Have separate carriageways for the two directions of traffic,
  - They are not crossed at the same level by other roads, footpaths, railways etc.,
  - Traffic entrance and exit is performed at interchanges only,
  - Have no access for traffic between interchanges and do not provide access to adjacent land,
  - Multiple and larger lanes,
  - No traffic light signals;
- **Urban/Suburban Roads:**
  - The general speed limit for urban roads in EU Member States is mostly 50 km/h,
  - Highest traffic flow,
  - Minimum distance between adjacent entrances/exits,
  - Serve not only motorised traffic, but also Vulnerable Roadside Users (VRU), such as pedestrians and bicycles,
  - Not frequent to find separate carriageways for the two directions of traffic,
  - Crossed at the same level by other roads, footpaths, railways etc.,
  - Single and multiple lanes. Mostly less large than motorways,
  - Many traffic light signals;
- **Rural Roads:**
  - The general speed limit for rural roads in EU Member States is mostly 80 or 90 km/h,
  - Traffic flow in between urban roads and motorways,
  - Distance between adjacent entrances/exits in between urban roads and motorways,
  - Serve not only motorised traffic, but also VRUs, such as pedestrians and bicycles,
  - Not frequent to find separate carriageways for the two directions of traffic,
  - Crossed at the same level by other roads, footpaths, railways etc.,

- Frequent access for traffic between interchanges and do not provide access to adjacent land,
- Single and multiple lanes,
- Some traffic light signals.

2.2 Tracks parallel to road

Figures 1 to 5 present different situations of tracks parallel to roads in the context of the different types of trains and roads. In the future, all vehicles could be autonomous and this will be addressed in Section 3.

Figure 1: HSL, regional line and rural road [7]

Figure 2: Main line and highway [8]

Figure 3: Regional line and rural roads [9]

Figure 4: Urban/Suburban line and roads [10]

Figure 5: Tramways and urban roads

Concerning the parallelism between the types of roads and tracks, there is no direct interconnection found on the literature. Therefore, this could mean that, for each type of track, all the different types of roads could eventually be found nearby.

Some criteria must be defined in order to consider a road parallel to a track such as the distance between them (minimum and maximum), horizontal and vertical planes parallelism, side-by-side distance, etc. In the definition of the various coexistence scenarios, it is also important to define how long tracks and road should stay side-by-side.

Another important point to be considered is the type of environment (open areas, rural areas, urban areas and dense urban areas) that can be found nearby this scenario, as it will have influence on the propagation of the wave signals.

In a more practical view, four types of environment can be defined:

- Open areas – No constructions nearby.
- Rural areas – Small number of constructions nearby.
- Urban areas – Higher number of constructions and small buildings can be found (small cities or at the big city entries).
- Dense urban areas – High amount of constructions and high-rise buildings can be found (big cities centres).

More detailed scenarios can be found in the literature when radio waves propagation is considered. For example, in [9] the scenarios are merged into 3 categories (relatively open scenarios, relatively closed scenarios and semi-closed scenarios) taking into account different radio channel characteristics of T2X and V2X.

In the “Tracks parallel to Road” scenario, no physical interaction between cars/vehicles and trains is found, which means that a direct communication between them is, probably, not essential as in the cross-level scenarios to prevent accidents.

Another case of tracks parallel to road is the urban scenario near a central railway station in a big city. This urban area is surrounded by high or medium size, sometimes old buildings, impacting the coverage conditions. Arrival/departure point of regional line is considered.

Figure 6: Example of topology of a central railway station (e.g. Gare du Nord, in Paris)

Figure 7: Surroundings and traffic view in the vicinity of Gare du Nord, in Paris

2.3 Tracks crossing road

2.3.1 Level Crossing

Figure 8: Level crossing in France [12]

Level Crossing (LC) corresponds to a specific coexistence case between trains and cars, in general for main lines and regional lines. It corresponds to the intersection between a road and a railway line, i.e. a crossing point between trains and cars. Level crossings do not exist in the context of high speed lines and highways. They are considered as a very weak point of railway infrastructure. Indeed, the safety of these crossings cannot be complete and accidents involving road users (drivers, pedestrians, etc.) are numerous [13]. On primary roads, barrier closure is used to indicate to road users the arrival of a train, thus guaranteeing a high level of safety and limiting the crossing risks. For some secondary roads, this arrival is only indicated by a light and/or sound warning (also used on primary roads), offering a lower level of safety.

Unlike the majority of the railway infrastructure, at level crossings, railway safety does not only depend only on the proper functioning of the railway system (warning, barriers), but also on the behaviour of road users. Any malfunction of the railway system or dangerous/unplanned behaviour of road users (stop on the LC, non-respect of the safety distance, non-respect of LC signalization, vehicle breakdown) could lead to accidents [14].

This is why the inclusion of technological solutions seems essential today to secure these level crossings and to monitor in real time the behaviour of road users [15]. A first technological step could be to deploy cameras at high-risk level crossings [15]. These cameras, coupled with an image analysis system [16] or with the assistance of an operator, could be used to detect the presence of obstacles on the railway line and to transmit this information to trains, limiting therefore the risk of collision. This type of service is usually based on information feedback from cameras to the railway server and a transmission of warnings to the trains via Train-to-Ground communications over cellular network.

The new types of communications currently designed in the rail and road environment (Vehicle-to-Vehicle, Vehicle-to-Infrastructure, etc.), the performance expected from 5G cellular networks [17], the deployment of a dedicated infrastructure for vehicle communications (ITS-G5 in Europe) and the associated idea of Cooperative Intelligent Transport Systems (C-ITS) [18], open up the perspective of more complex, and more complete, technological solutions.

In this way, many European projects, such as the InDiD [19] and C-Roads projects [20], are looking at the use of Vehicle-to-Infrastructure communications to make level crossings safer. Indeed, in these projects it is proposed to use the data generated and transmitted by the cars (position, speed, status, etc.) to verify that the crossing level can be traversed by the train. To exchange information between cars and trains, these projects rely on an interconnection between road and rail servers. Thus, information is transmitted from the car to the road server, then to the rail server and finally to the train. Going further, the use of direct communications between trains and cars (Vehicle-to-Vehicle), or relayed by the roadside infrastructure (Vehicle-to-Infrastructure, Infrastructure-to-Vehicle), could be envisioned to ensure low latency and to manage emergency situations.

Thus, the coexistence of rail and road, at level crossings, is primarily physical. The infrastructure is unique and has to be shared between the different vehicles. Communication between trains and cars appears to be a potential solution to limit the risk of accidents at these level crossings, enabling to check the presence or absence of obstacles on the line. However, road and rail services are not only dedicated to level crossing safety. Indeed, there are many other applications specific to the automotive domain (autonomous car, platooning, High Definition maps, etc.) and to the railways domain (coupling of trains, remote driving, etc.). All these services could rely on the use of a common public 5G communication infrastructure (radio access network, core). Therefore, the coexistence of road and rail services also exists at the communication infrastructure level. Indeed, it must ensure the proper functioning of road and rail services regardless of the situation (density, speed, etc.) and the environment (urban, suburban, and rural) considered. This is another important point to consider.

2.3.2 The case of tramways

Figure 9 to Figure 12 show several examples of urban coexistence intersections shared by different means of transport (trams, buses, cars, among others) in different Spanish cities. The traffic needs in such crowded and dynamic urban scenarios, require a robust and coordinated operation between all the involved urban rail and road applications.

Figure 9: Intersection between tram and road traffic in the city of Zaragoza (Spain)

Figure 10: intersection between tram and road traffic in the city of Barcelona (Spain)

Figure 11: intersection between tram and road traffic in the city of Barcelona (Spain)

Figure 12: intersection between tram and road traffic in the city of Barcelona (Spain)

Figures 12 and 13 give examples of accidents that prove the needs of coordination between rail and road traffic in urban dense areas.

Figure 13: Example of accident in an urban coexistence scenario between a tram and a van in the city of Vitoria (Spain)

Figure 14: Example of accident in an urban coexistence scenario between a tram and a car in Cadiz (Spain)

2.4 Tunnels and bridges

Regarding tunnels, the most usual configuration is tunnel sections devoted for railway tracks sharing the same horizontal plane with tunnel sections devoted for road lanes ("single deck"). Usually separated tunnels are used for each direction, for isolation and safety concerns, as illustrated in Figure 15.

Figure 15: Examples of shared tunnel section [21]

Tunnels with differentiated parallel sections, in the vertical plane, so called "double deck", for road and railway are not usual, as the vertical work, in depth, carries more complexity and costs than working in broadness at the same level. Therefore. the cross section represented in the Figure 15 is preferred to that in Figure 16, for tunnels.

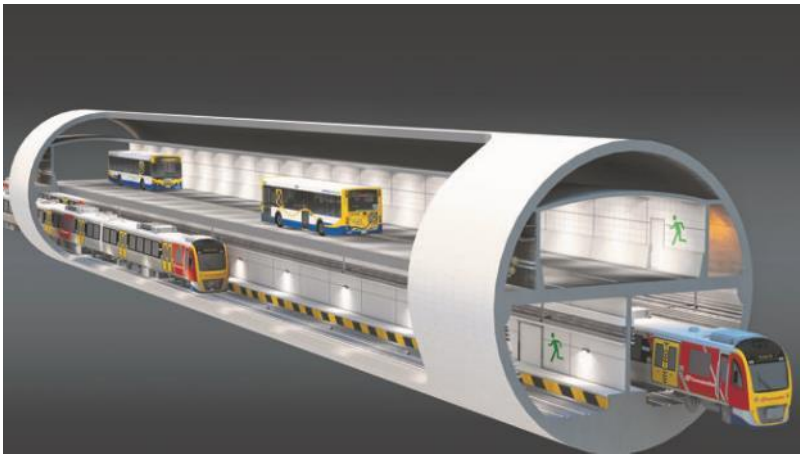

Figure 16: Double deck tunnel example [22]

Taking this as a valid discrimination argument, single deck tunnels, with parallel lanes for road and railway tracks will be assumed as the case for tunnels in the following. In this regards, the considerations for the case "tracks parallel to the road" in Section 2.2 could apply, but careful care needs to be given to the effects of the construction materials and its filtering effects, in case that common access deployments are to support these coexistence scenarios.

Another case where tunnels may be relevant is the case in which the tunnel runs below a railway or road surface infrastructure. This scenario could be considered similar to the "level crossing" and "tramway in urban area" scenarios, in Sections 2.3.1 and 2.3.2, where one of the elements (road or railway track) is underground, while the other (railway track or road) is on the surface. As mentioned, the specific differential value of the scenario will be imposed by the material composition and the depth of the tunnel, i.e. the cross section distance between road and track, which will affect the attenuation of the radiation and act as a natural filter against interferences or an attenuator for common access transmissions.

Finally, a special multiple case for tunnels is the situation for Metro infrastructure in urban areas, where multiple tunnels coexist with road infrastructure, as illustrated in Figure 17.

Figure 17: Multilevel tunnelling description [23]

Regarding Viaducts or Bridges, the preferred cross-section distribution seems to be the opposite to that of tunnels: usually road and tracks are discriminated in two different vertical planes, in a double deck, as illustrated in the Figure 18. This seems to be due to minimize the broadness of the bridge deck.

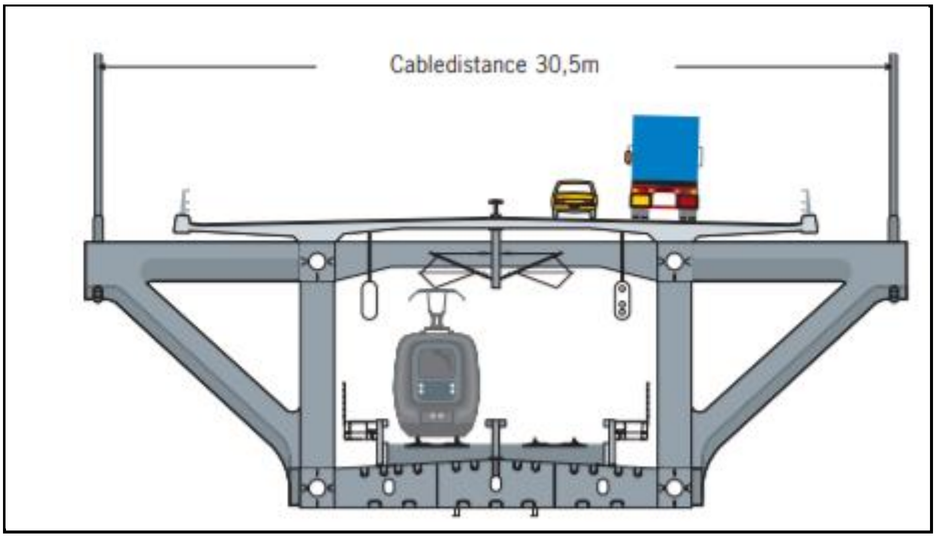

Figure 18: Example of Cross section for a bridge shared by road and railway [24]

This tends to be especially relevant for long bridges, as the case of shared horizontal plane, in a single deck, appears more often in short length bridges, as illustrated in Figure 19.

Figure 19: Example of Bridge with Rail and Road on the same plane [25]

Having the road level above the railway level provides some isolation to the railway tracks from weather phenomena, therefore the scenario presented in Figure 18 will be assumed as an example for this case, from now and on. This scenario could be described as well as a special case of the scenarios discussed in Section 2.2, where special consideration should be given to the access technology, antenna directionality, radiation side-lobes, etc.

As in the case of tunnels, other scenarios where a bridge/aqueduct crosses a road lane or railway track could be analysed, as illustrated in Figure 20. Again, these cases could be considered as special cases of other cases presented in this document.

Figure 20: Example of road and train coexistence by elevated aqueduct [26]

Finally, in large infrastructure projects, it is possible to have both cases of bridges and tunnels combined in different sections of the same infrastructure. As an example, the Øresund Bridge, connecting Denmark and Sweden with a 25 km long link, it is a combination of Tunnel and Bridge as illustrated in Figure 21.

Figure 21: Example of Tunnel and Bridge combined on the same infrastructure [27], [28]

3 AUTONOMOUS AND CONNECTED VEHICLES

As part of the definition of rail/road urban coexistence scenarios, not only the interaction between rail and road systems in present operation should be considered, but also the imminent presence of **driverless autonomous/automated trains and cars** in innovative urban scenarios.

The autonomous driving (AD) vehicle is always mentioned together with the term of **connected vehicle.** So far, several demonstrations and even some products are available in the market showing the feasibility of the autonomous driving under certain circumstances. The AD is fully supported by embedded electronics (lidar, radar, cameras, etc.), but it is widely accepted that the limitations of the embedded sensors have to be complemented by wireless connectivity. In order words, even if the vehicle has many on-board sensors, they can only perceive local environment, which is why it is needed to add a wireless communication service (between vehicles and between vehicles and infrastructure) as “a new extended sensor” to get information beyond the local environment, and thus to get a future fully AD solution [29].

This opportunity is in the core of the new specification methodology of 5G, which will be able to boost existing services and to enable new ones, which nowadays are not possible or not optimized with the current cellular technologies. In the case of AD, 5G will enable the vehicle towards higher automated levels, since it provides an independent information source and contributes to perform more efficient data and sensor fusion. Besides, 5G radio technologies can complement existing positioning solutions based on GNSS, which may become crucial for autonomous driving.

Figure 22 depicts an example of autonomous train running on different urban scenarios of the Chinese city of Yibin. The ART (Autonomous Rail Rapid Transit) railway system uses a sensor-based network instead of traditional rails, and it does not require the use of catenary. The ART runs on a track whose lines are painted on the road in a discontinuous manner (virtual rails). To that end, the set of on-board sensors enable the ART to calculate the dimensions of the road and to follow the specific asphalt lines that trace its route. In addition, an intelligent communication system will guide the train through the streets in cooperation with traffic signals, in order to establish the right-of-way and obtain real-time traffic information to modify its route and avoid traffic jams.

Figure 22: Examples of urban coexistence scenario: autonomous train running on different urban scenarios of the Chinese city of Yibin

Figure 23 and Figure 24 show other interesting urban scenarios where autonomous trams are expected to operate in the near future, in continuous communication/cooperation with autonomous cars and buses.

Figure 23: Example of urban coexistence scenario: autonomous tram running on an urban bridge in the presence of dense road traffic

Figure 24: Example of urban coexistence scenario: autonomous train running on an urban roundabout

It is worth highlighting that **a level of automation may be used by road vehicles and a distinct one by railway systems.** Indeed, the normative ruling the definition of automation levels in automotive and railways is different. On the one hand, in the automotive sector, SAE J3016 regulation provides a taxonomy with detailed definitions for six levels of motor vehicle automation, ranging from no driving automation (level 0) to full driving automation (level 5) [30]:

- Level 0: No driving automation.
- Level 1: Driver assistance.
- Level 2: Partial driving automation.
- Level 3: Conditional driving automation.
- Level 4: High driving automation.
- Level 5: Full driving automation.

These levels of automation can be classified into two main groups: those related to Advanced Driver Assistance Systems (ADAS; levels 0, 1 and 2), and those related to autonomous/automated driving (levels 3, 4 and 5).

In its original version in 2014, SAE J3016 was based on previous work developed by the German Federal Highway Research Institute (BASt) and the National Highway Traffic Safety Administration (NHTSA). The table below shows the taxonomy defined by SAE J3016 in its first version, along with a comparison with BASt and NHTSA levels.

Table 1: Automation levels according to SAE J3016 regulation (original version, 2014) [31]

Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of *dynamic driving task*	System capability (*driving modes*)	BASt level	NHTSA level
Human driver monitors the driving environment								
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a	Driver only	0
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes	Assisted	1
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	System	Human driver	Human driver	Some driving modes	Partially automated	2
Automated driving system ("system") monitors the driving environment								
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task* with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	System	Human driver	Some driving modes	Highly automated	3
4	High Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	System	Some driving modes	Fully automated	3/4
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	All driving modes	-	

On the other hand, in the railway sector, IEC 62290 standard specifies the functional, system and interface requirements for command, control and management which are used in urban rail-guided passenger transport lines and networks [31]. In this case, five levels of automation are defined, ranging from manual operation to fully automated operation, and these levels can cover the whole line or only part of the line. Thus, the functions used are based on the specific Grade of Automation (GoA), taking into account the Grade of Line (GoL), which is defined by the line conditions considering relevant factors such as the traffic density and the train speed. In consequence, different GoAs may be used with the same train in different areas of the same line:

- GoA 0: Manual operation with no automated train protection.
- GoA 1: Manual operation with automated train protection.
- GoA 2: Semi-automated train operation.
- GoA 3: Driverless train operation.
- GoA 4: Unattended train operation.

The table below summarizes the basic train operation functions required for the different GoA levels.

Table 2: Grades of automation in railways according to IEC 62290 standard [31], [32]

Basic functions of train operation		On-sight	Non-Automated	Semi-Automated	Driverless	Unattended
		GOA0	GOA1	GOA2	GOA3	GOA4
Ensure safe movement of trains	Ensure safe route	Ops Staff (route by systems)	Systems	Systems	Systems	Systems
	Ensure safe separation of trains	Ops Staff	Systems	Systems	Systems	Systems
	Ensure safe speed	Ops Staff	Ops Staff (partial by system)	Systems	Systems	Systems
Drive train	Control acceleration and braking	Ops Staff	Ops Staff	Systems	Systems	Systems
Supervise guideway	Prevent collision with obstacles	Ops Staff	Ops Staff	Ops Staff	Systems	Systems
	Prevent collision with persons on tracks	Ops Staff	Ops Staff	Ops Staff	Systems	Systems
Supervise passenger transfer	Control passengers doors	Ops Staff	Ops Staff	Ops Staff	Ops Staff	Systems
	Prevent injuries to persons between cars or between platform and train	Ops Staff	Ops Staff	Ops Staff	Ops Staff	Systems
	Ensure safe starting conditions	Ops Staff	Ops Staff	Ops Staff	Ops Staff	Systems
Operate a train	Put in or take out of operation	Ops Staff	Ops Staff	Ops Staff	Ops Staff	Systems
	Supervise the status of the train	Ops Staff	Ops Staff	Ops Staff	Ops Staff	Systems
Ensure detection and management of emergency situations	Detect fire/smoke and detect derailment, detect loss of train integrity, manage passenger requests (call/evacuation, supervision)	Ops Staff	Ops Staff	Ops Staff	Ops Staff	Systems and/or staff in OCC

The main difference between SAE J3016 and IEC 62290 standards lies in the fact that, in the automotive domain, the classification refers to the automation of activities performed by the driver, while in the railway domain, automation covers functions performed not only by the driver but also by operators located on the platform or in the OCC (Operation Control Centre). Table 3 shows the equivalence between the different levels/grades of automation established by both standards.

Table 3: Equivalence between the different levels/grades of automation established by SAE J3016 and IEC 62290 standards

<table>
<tr><th>SAE J3016 Level</th><th>IEC 62290 GoA</th></tr>
<tr><td>Level 0: No driving automation</td><td>GoA 0: Manual operation with no automated train protection</td></tr>
<tr><td>Level 1: Driver assistance</td><td>GoA 1: Manual operation with automated train protection</td></tr>
<tr><td>Level 2: Partial driving automation</td><td>GoA 2: Semi-automated train operation</td></tr>
<tr><td>Level 3: Conditional driving automation</td><td rowspan="2">GoA 3: Driverless train operation</td></tr>
<tr><td rowspan="2">Level 4: High driving automation</td></tr>
<tr><td rowspan="2">GoA 4: Unattended train operation</td></tr>
<tr><td>Level 5: Full driving automation</td></tr>
</table>

NOTE: The synergy between both standards is important for specific cases, such as trams and their similarity to buses. Although it is clearly defined that tram automation levels are within the scope of IEC 62290, and bus automation levels within the scope of SAE J3016, it is true that some specific functions required in both systems fall into a zone where each one can take advantage of the advances of the other:

- In the case of trams, since they move in a less controlled environment than a conventional train, the environmental sensing technology being developed for buses will be of great use, including sensors and data processing for identification of obstacles and other actors. Similarly, some of the functionalities to which SAE J3016 applies may also be useful, such as driving in heavy traffic (Traffic Jam Assist), adapting speed to the flow of vehicles ahead (Adaptive Cruise Control, ACC), among others.
- In the case of buses, several of the functions related to passenger handling (doors operation, vehicle diagnostics, etc.) included in IEC 62290 are also susceptible to automation.

4 DESCRIPTION OF DOMAIN SPECIFIC COMMUNICATION SERVICES

4.1 Specific communication services for automotive

Different communication services can be defined in the automotive domain: road safety, traffic management and road experience. These services can have different levels of criticality depending on their importance for road safety. Consequently, there are different needs in terms of communication performance. The development of automation requires more advanced and safe services such as: Dynamic lane management, Automated Driving, Vehicle Platooning, Remote Driving, etc. Such kind of services are considered highly critical regarding road safety. This criticality implies strict needs in terms of network communications performance. Consequently, C-ITS shall allow the cohabitation of all the services (safe, non-safe and highly critical), taking into account their heterogeneity. Table 4 presents the different characteristics of some example of services in the automotive domain.

Table 4: Communication services for automotive [33]

Service (example)	Latency	Data Rate/Frequency (Uplink-UL/Downlink-DL)	Reliability	Type of communications (V2V, V2I, V2P, *etc.*)	Type of message
Autonomous Navigation (HD Map Local Acquisition)	30 ms	1 Mbps (UL)/ 2,88 Mbps (DL)	0,99	V2V, V2I	CAM, DENM, CPM
Remote Driving (Automated parking)	50 ms	14 Mbps (UL)/ 6 Mbps (DL)	0,99999	V2I	-
Cooperative Maneuver (Lane merge)	60 ms	128 kbps	0,99	V2V	MCM, PCM
Cooperative Perception (See Through)	50 ms	14 Mbps (UL)/ 14 Mbps (DL)	0,99	V2V	CAM, DENM, CPM
Cooperative Safety (Vulnerable Pedestrian Protection)	30 ms	128 kbps	0,9999	V2V, V2I, V2P	VAM, CPM
Infotainment (UDH Video)	500 ms	15 Mbps	-	V2V, V2I	-
Remote diagnostics	-	-	-	V2I	-

Two of the most promising wireless technologies developed for C-ITS services to support vehicular communications for road applications are ITS-G5 and LTE-V2X, which can be also extended to railways (i.e. to an environment in which both railway systems and road vehicles are interconnected).

On the one hand, ITS-G5 is the European standard for vehicular communications proposed by ETSI. Specifically, it is a microwave radio technology composed of latency-critical communication methods based on IEEE 802.11p.

On the other hand, LTE-V2X technology proposed by 3GPP is an extension of Long Term Evolution cellular technology for vehicular communications. Namely, it is a derivative of the cellular uplink technology, that maintains similarity with the current LTE systems: frame structure, sub-carrier spacing, clock accuracy requirements and the concept of a resource block, among others. This technology supposes an important step of the cellular-based technology in addressing safety-critical requirements, but it is not yet at the level of ITS-G5 (IEEE 802.11p).

A strong cellular ecosystem leverages years of experience in providing paid-services and a mature technology available worldwide, but it refers mostly to entertainment services in a cellular-based technology, being the communication between a device and a base-station fundamentally different from the device-to-device communication in a dynamic environment.

Furthermore, the following technical features of LTE-V2X must be highlighted: it suffers when there is no network to support the communications, it has stringent synchronization requirements, it cannot properly receive messages from nearby and closed-by transmitters, and it is limited in its maximum range. In addition, it proposes a resource allocation scheme that does not properly handle messages with variable size, and a multiple user access mechanism that is not well suited for broadcasting messages or for handling collisions of messages.

In conclusion, there are several relevant facts important to highlight when comparing ITS-G5 to LTE-V2X [34]:

- ITS-G5 access technology is based on IEEE 802.11p protocol. IEEE 802.11p-based products are available on the market. In contrast, LTE-V2X has not evolved in the similar way, so it will take several years before a complete solution will be ready and tested.
- IEEE 802.11p technology is ideal for safety-critical and life-saving applications that must be supported in absence of a network. However, if the cellular infrastructure is available, LTE-V2X is a valid alternative for V2X services, thus leveraging the years of innovations in the cellular domain.

The win-win situation would be to focus on the strongest points of each technology, working together in order to provide the best V2X communication solution by continuing deploying IEEE 802.11p for safety-critical applications and by ensuring that the upcoming LTE-V2X technology can coexist.

As a final remark, 5G will also propose another solution for V2X in the second release of 5G NR, allowing significant improvements in terms of latency, throughput and reliability, as well as the development of more robust applications related to automatic train, control-command, maintenance, remote control of trains, positioning, etc. This may cause that automotive and train companies will be reluctant to embark on other technologies (such as ITS-G5 and LTE-V2X) that will be obsoleted soon by 5G. Nonetheless, it should be taken into consideration that the promised 5G version of V2X will have an even longer time horizon than LTE-V2X.

4.2 Specific communication applications (services) for railways

The terminology “services” and “applications” is explained in the definition section at the beginning of the document. In the railway domain, the term “applications” is mainly used. In the road domain, the term “services” is considered.

4.2.1 Future Railway Mobile Communication for train operation

Based on the FRMCS user requirements’ specifications document, owned by UIC, there are three kinds of railways services and associated applications: **critical, performances and business ones.** This categorization depicts the needs of railway operators, but also induces requirements and implementation constraints to be fulfilled by the transport stratum, including access and core network. This approach was our guideline for the selection of use cases within Work Package 1 of 5GRAIL. The list of the selected use cases is presented in the § 10 Appendices.

Critical applications are mandatory for the railway operations and encompass the harmonised communications, because information generated in this type of services must be shared between different stakeholders, e.g., infrastructure operators and several railway operators. Indicative applications of this type are related to train operation/movement (ATC), railway automation systems (ATO), trackside maintenance, emergency voice communications (REC) and safety services Mission Critical Push to Talk (e.g. point-to-point calls between the controller(s) of the train/ operations centre and the driver/ on-train staff etc.), group calls between train drivers in a predefined area including ground users.

Performance applications are non-critical services related to train operation. In general, these can be sub-grouped into telemetry services, infrastructure monitoring and maintenance services. The use cases are focused on CCTV (Close Circuit TeleVision) services for supervision of the rail tracks quality and provision maintenance when needed. Cameras mounted on the front and rear part of the train capturing images that are forwarded in real time to the Operations Centre (of the railway facilities) are examples of this kind of services.

Business applications are services supporting the railway business operation in general that are usually provided to passengers requiring communication services and broadband connectivity when embarking, travelling, and disembarking from the trains daily. Related applications are not included in the selected list of 5GRAIL.

The FRMCS architecture principle is based on decoupling of applications, services, and transport stratum. FRMCS is compliant with 5G technology (access and core). Besides that, allowing neutrality of radio access technology together with 3GPP 4G/5G standards provide tailored to the specific services requirements and deployment challenges that fulfil the expectations of railway stakeholders [35]. Figure 25 presents the coexistence of the three kinds of railway services over 5G infrastructure:

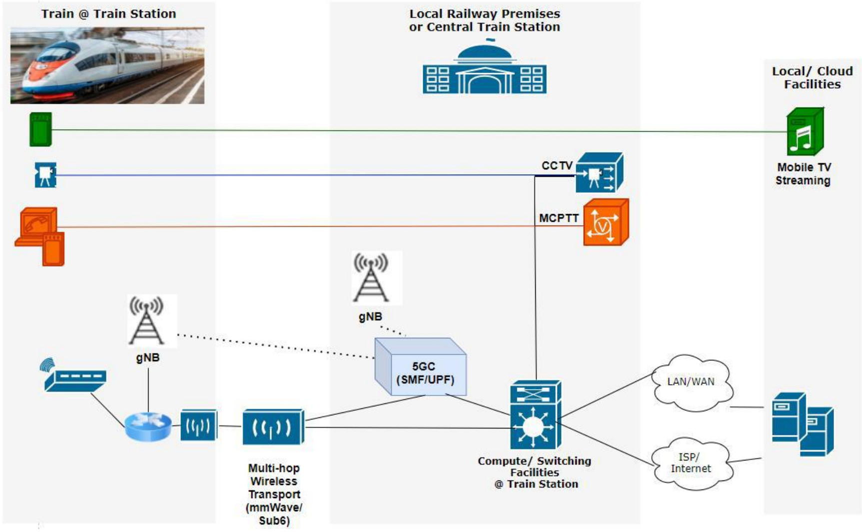

Figure 25: Critical, Performance and Business Services over 5G infrastructure at Railway Facilities

In the 3GPP TS 22.289 V17.0.0 (2019-12) document, the main communication characteristics in terms of the so called Key Performance Indicators (KPI) of different railway applications, depending on market segment, are given. Table 4 summarizes the KPI for main lines at application level in terms of end-to-end latency, data rate, reliability, message size, etc. All the applications are mapped into the FRMCS use cases as they are described in [36].

4.2.2 Virtual coupling

The virtual coupling of train sets (VCTS) will consist in replacing the mechanical coupling of trains used today by the cooperative movement of trains running on the same line. The concept is equivalent to platooning in the automotive domain. It will allow to create longer trains based on the coupling of two or more train sets [37], [38], [39]. Very similarly, to the automotive domain, the VCTS concept leverages cooperative movement, which relies on mutual exchange of relevant information such as speed, location, braking curve, among train sets. It allows trains to run at a closer distance than that allowed by traditional Absolute Braking Distance Supervision (ABDS) concept as illustrated in Figure 26 [37]. VCTS might be a disruptive innovation in railway system. It will overcome and replace the old system with cooperative system view, where intelligence and relevant information are distributed amongst the moving units within the system. This concept will increase efficiency, operational flexibility, line capacity, competitiveness among market players and quality of consumer experience. Train-to-Train (T2T) and Train-to-Ground (T2G) wireless communications will be the backbone for the implementation of the virtual coupling functionalities [37]. For main line, the 3GPP document also defined the KPI requirements for VCTS, which are summarized in Table 5 and Table 6.

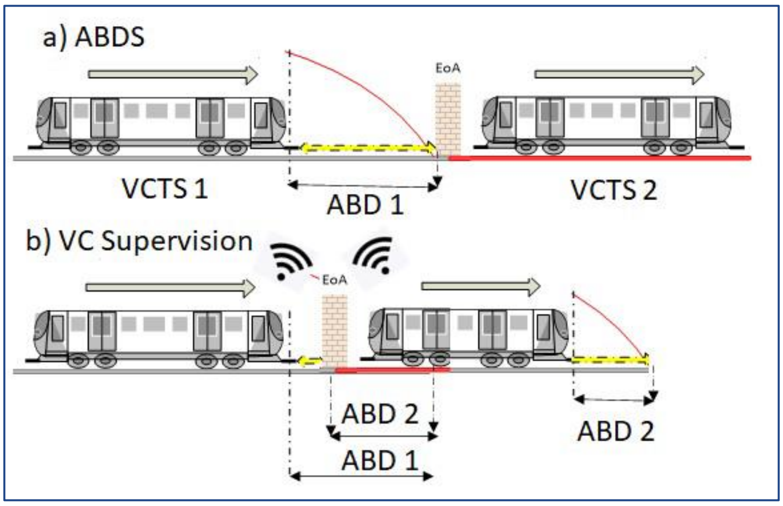

Figure 26: Virtual coupling: relative braking distance [37]

Table 5: Main communication characteristics for applications related to main lines (3GPP TS 22.289 V17.0.0 (2019-12)

Scenario	End-to-end latency	Reliability (Note 1)	Speed limit	User experienced data rate	Payload size (Note 2)	Area traffic density	Service area dimension (note 3)
Voice Communication for operational purposes	≤100 ms	99,9%	≤500 km/h	100 kbps up to 300 kbps	Small	Up to 1 Mbps/line km	200 km along rail tracks
Critical Video Communication for observation purposes	≤100 ms	99,9%	≤500 km/h	10 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks
Very Critical Video Communication with direct impact on train safety	≤100 ms	99,9%	≤500 km/h	10 Mbps up to 20 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks
	≤10 ms	99,9%	≤40 km/h	10 Mbps up to 30 Mbps	Medium	Up to 1 Gbps/km	2 km along rail tracks urban or station
Standard Data Communication	≤500 ms	99,9%	≤500 km/h	1 Mbps up to 10 Mbps	Small to large	Up to 100 Mbps/km	100 km along rail tracks
Critical Data Communication	≤500 ms	99,9999%	≤500 km/h	10 kbps up to 500 kbps	Small to medium	Up to 10 Mbps/km	100 km along rail tracks
Very Critical Data Communication	≤100 ms	99,9999%	≤500 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 10 Mbps/km	200 km along rail tracks
	≤10 ms	99,9999%	≤40 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 100 Mbps/km	2 km along rail tracks
Messaging	-	99.9%	≤500 km/h	100 kbps	Small	Up to 1 Mbps/km	2 km along rail tracks
NOTE 1: Reliability as defined in sub-clause 3.1. NOTE 2: Small: payload ≤ 256 octets, Medium: payload ≤512 octets; Large: payload 513 -1500 octets. NOTE 3: Estimates of maximum dimensions.							

Table 6: KPI for very critical communications in main lines scenarios

Scenario	End-to-end latency	Reliability (Note 1)	Speed limit	User experienced data rate	Payload size (Note 2)	Area traffic density	Service area dimension (Note 3)	Max required communication range (meters) (Note 4)
Very Critical Data Communication	≤100 ms	99,9999%	≤500 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 10 Mbps/km	3 km along rail tracks	[1000 ~ 3000]
	≤300 ms	99,9%	≤40 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 100 Mbps/ km	3 km along rail tracks	[1000 ~ 3000]
NOTE 1: Reliability as defined in sub-clause 3.1. NOTE 2: Small: payload ≤ 256 octets, Medium: payload ≤512 octets; Large: payload 513 -1500 octets. NOTE 3: Estimates of maximum dimensions. NOTE 4: Relevant for Off-Network MCData Service only, supporting train platooning. All trains in a platoon are driving in the same direction.								

4.2.3 Urban rail

Finally, Table 7 gives the KPI for critical applications in the case of mass transit or urban rail.

Table 7: Characteristic parameters (KPIs) of communication service performance requirements for rail-bound mass transit

	Characteristic parameters				Influence parameters						
Use case	Communication service availability: target value (note 1)	Communication service reliability: mean time between failures	End-to-end latency: maximum (note 2)	Service bit rate: user experienced data rate	Communication pattern	Message size	Transfer interval: target value	Survival time	UE speed	# of UEs	Service area (note 3)
1: Control of automated train (note 4)	99,999 %	below 1 year but >>1 month	<100 ms	≥200 kbit/s	periodic deterministic	≤ 200 bytes	100 ms	~500 ms	≤160 km/h	<25	50 km x 200 m
2: CCTV communication service for surveillance cameras (note 4)	>99,99 %	~1 week	<500 ms	≥2 Mbit/s	aperiodic deterministic			~500 ms	≤160 km/h	<25	50 km x 200 m
3: Emergency voice call (note 4)	>99,99 %	~1 day	<200 ms	≥200 kbit/s	aperiodic deterministic			~2 s	≤160 km/h	<25	50 km x 200 m
4: Train coupling	>99,9999 %	~1 year	<100 ms	1 Gbit/s	mixed traffic			~500 ms	– (note 5)	2	3 m x 1 m
5: CCTV offload in train stations				≥1 Gbit/s	non-deterministic				~0 km/h	≥1	train station

NOTE 1: One or more retransmissions of network layer packets may take place in order to satisfy the communication service availability requirement.
NOTE 2: Unless otherwise specified, all communication includes 1 wireless link (UE to network node or network node to UE) rather than two wireless links (UE to UE).
NOTE 3: Length x width.
NOTE 4: 2 UEs per train car, column “# of UEs" is per train, there are multiple trains in the given service area.
NOTE 5: UE speed is irrelevant since this communication takes place between two train segments.

4.2.4 Train Control and Monitoring System

The Train Control and Monitoring System (TCMS) is an on-board system built with the purpose to control and monitor a list of train equipment and functional processes. Based on a control and monitoring architecture, TCMS centralises all the information related to the operating status of all of the so-called “intelligent” train equipment.

The purpose of the Train Control and Monitoring System application is to collect telemetry data from on-board train systems and send them to the ground via wireless connectivity. These data can be used by various systems employed by Railway Undertakings or Infrastructure Managers to increase performance or support the management of day-to-day operations. In case of proximity of railway and road infrastructure, interactions between rail and road systems may be possible. Example of this kind of data can be:

- Vital parameter condition and onset of fault condition data from intelligent on-train systems to train maintenance infrastructure.
- Transfer of infrastructure condition data from on-board sensors or cameras, which monitor the condition of trackside infrastructure as the train moves along the track, to infrastructure maintenance depots or operations control centres.
- Information on the load of the train (e.g. container), like position and load status.
- Information on the railway asset (e.g. wagon), like position and status.
- The transfer of configuration data to the on-board train systems.

Four types of communication can be distinguished: intra-vehicle, intra-consist, consist-to-consist (called inter-consist), and train-to-train. In addition, there is a fifth type of communication link: train-to-ground (T2G). The Roll2Rail project [40] specified the requirements for a wireless TCMS. This is still under development in the Safge4rail3 project [41].

5 COEXISTENCE FROM A TELECOMMUNICATION POINT OF VIEW

5.1 Introduction

Different rail/road urban coexistence proof of concept trials from the telecommunication point of view are currently being developed. As an example, in Czech Republic, several pilots have been recently conducted for the public transport deployment in cities of Ostrava and Plzen [42], [43], [44], where C-ITS services were offered via a hybrid ITS-G5/LTE-based system. Namely, the public transport companies of cities of Ostrava and Plzen, together with project partner Intens, were responsible for ITS-G5 deployment, whereas the LTE-based services were offered by the mobile phone operators O2 and T-Mobile. Intens installed RSUs (Road-Side Units) in Pilsen (1 RSU) and Ostrava (5 RSUs), being one OBU (On-Board Unit) deployed to a public transport vehicle in Ostrava. Firstly, this OBU was installed on a bus, and then on a tram. The aim of these pilots was to improve the safety of urban rail and road systems without compromising the regularity of trams, taking into consideration that trams shall communicate with road users in order to be ready for the arrival of autonomous vehicles. For that purpose, the pilots covered different city streets/roads and intersections with tram rail infrastructure. Suitable junctions equipped with traffic lights were selected for public transport priority use case, and critical collision points between public and individual transports were identified for deployment of safety-related applications.

The concept of coexistence of rail and road, from the point of view of telecommunication, may imply many different situations in which different wireless technologies are used in a disaggregated way or in a cooperative way. This can imply telecommunication infrastructure sharing or not. Consequently, there will be a huge number of possible coexistence scenarios related to the different scenarios previously highlighted from the infrastructure point of view (Section 2). In this section, the topic of radio coexistence taking into account spectrum allocation and interferences will be detailed. Then, the coexistence at backhaul and core network level will be addressed. It is worth noting that the definition and identification of coexistence scenarios between road and rail will follow a rigorous methodology, which can be found in Section 6.

5.2 Radio coexistence / Electromagnetic compatibility

In recent years, the Urban Rail community has proposed and pushed to use the **spectrum allocated to the road ITS systems in the band 5.9 GHz for the use of urban rail ITS systems in big cities.** The deployed communication systems are proprietary and they do not follow any harmonised specification. A sharing between urban rail ITS systems and the existing road ITS systems can only be reached by **complex mitigation and sharing techniques.**

In October 2017, the CEPT received the mandate from Radio Spectrum Committee (RSCom) of the European Commission to study the extension of the Intelligent Transport Systems safety-related band at 5.9 GHz [30]:

1. Study the possibility to **extend the 5875-5905 MHz frequency band to the range 5875-5925 MHz for use by safety-related road and rail ITS systems under harmonised technical conditions including sharing conditions.** In this context, study measures which allow

coexistence of LTE-V2X and urban rail ITS with existing ETSI ITS-G5 within the 5875-5925 MHz frequency band.

2. Assess the suitability of the existing harmonised technical conditions applicable to the 5875-5905 MHz frequency band for use by urban rail ITS. Amend these conditions, if necessary, so as to develop consistent technical (including sharing) conditions for the whole 5875-5925 MHz frequency band. This should not result in segmentation and segregation of the band. The principle of **equal access to shared spectrum** shall be applied taking into account the need to **avoid harmful interference** and the need for reliable safety-related operation in the whole band.

In summary, the radio coexistence is intended to allow both urban rail and road ITS systems to **rely on the same frequency band and infrastructures,** which would significantly simplify the sharing operation and could **reduce the cost of urban rail systems** due to the reuse of existing telecommunications resources. Hence, it constitutes a necessity from a budgetary point of view but also from an energy and spectral point of view.

The radio coexistence analysis that will be shown in the following subsections will revolve around the fact that ITS-G5 and LTE-V2X communication systems are foreseen to coexist in this same band of 5875-5925 MHz. A proposal for spectrum sharing by urban rail and road ITS systems can be found in the report presented in [45], which gives an initial evaluation of the required changes and extensions in the ETSI ITS standards and specifications. Therefore, it can serve as a basis for further development and standardisation work in the field of rail communication, with the focus on urban rail systems.

5.2.1 Regulation in the 5.9 GHz band

The usage of the 5.9 GHz band over IEEE 802.11p access mode, was defined by ETSI [45] as ITS-G5 A, D, B and C for safety-critical, non-safety-critical and general traffic applications, respectively [45]:

- ITS-G5A: 5875 MHz to 5905 MHz – ITS safety (not limited to road safety).
- ITS-G5B: 5855 MHz to 5875 MHz – ITS non-safety.
- ITS-G5D: 5905 MHz to 5925 MHz – Other future ITS applications.
- ITS-G5C: 5470 MHz to 5725 MHz – RLAN.

The European ITS frequency allocation scheme is shown in Figure 27, along with the channel allocation (Table 8). The usage of G5-SCH1, G5-SCH2 and G5-CCH channels are dedicated for ITS safety applications, which pose severe requirements on the reliability and the latency of the data transmission.

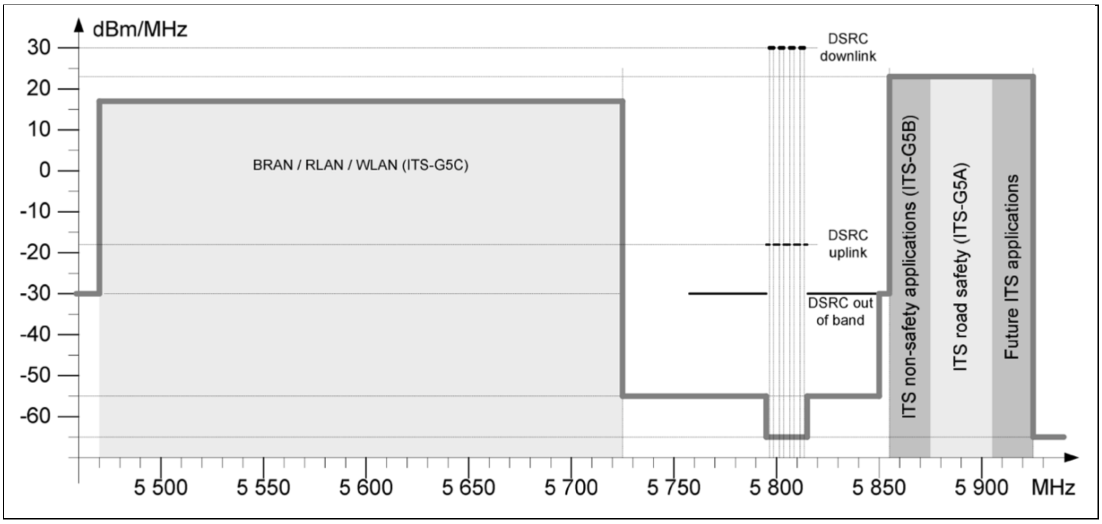

Figure 27: European ITS frequency allocation repartition in the spectrum [46]

Table 8: European ITS channel allocation scheme [45]

Channel type	Centre frequency	IEEE 802.11 channel number	Channel spacing	Default data rate
G5-CCH	5 900 MHz	180	10 MHz	6 Mbit/s
G5-SCH2	5 890 MHz	178	10 MHz	12 Mbit/s
G5-SCH1	5 880 MHz	176	10 MHz	6 Mbit/s
G5-SCH3	5 870 MHz	174	10 MHz	6 Mbit/s
G5-SCH4	5 860 MHz	172	10 MHz	6 Mbit/s
G5-SCH5	5 910 MHz	182	10 MHz	6 Mbit/s
G5-SCH6	5 920 MHz	184	10 MHz	6 Mbit/s
G5-SCH7	As described in ETSI EN 301 893 for the band 5.470 MHz to 5.725 MHz	94 to 145	Several possibilities	dependent on channel spacing

Several changes were proposed for this frequency allocation. Namely, the Urban Rail proponents in ETSI and CEPT agreed a spectrum need of 20 MHz split into 4 x 5 MHz channels, in such a way that the **urban rail application will have a certain prioritisation in the upper 20 MHz of the ITS band (5905 MHz to 5925 MHz),** as long as the planned ITS application can still use the bands with only limited restrictions. Figure 28 depicts the proposed prioritisation of the spectrum.

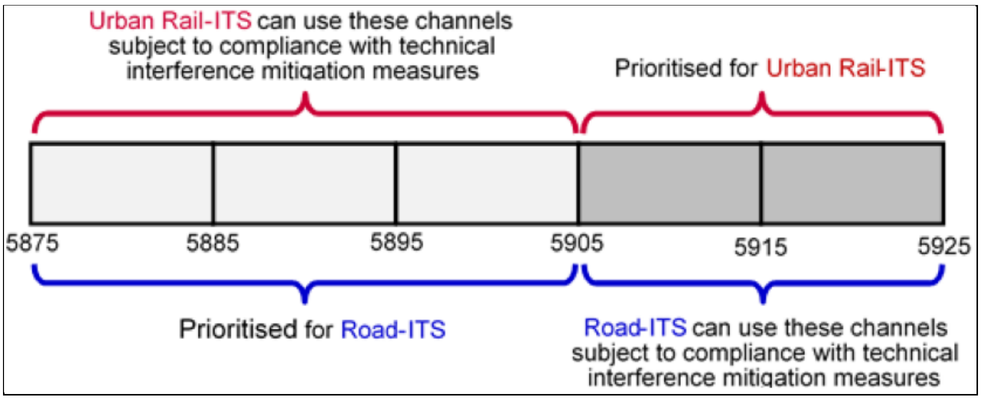

Figure 28: Proposal for prioritisation mechanism [47]

In order to be able to respect the prioritisation of urban rail applications in the band 5905 MHz to 5925 MHz, it is important that a road ITS system gets the dynamic information about the sharing needs of urban rail based on the actual traffic situation.

As a remark, it is worth noting that it is under discussion the possible use of the band 5925 MHz to 5935 MHz by urban rail ITS. It can be a decisive factor that current implementations of urban rail radio systems under individual authorisations are already using the band 5925 MHz to 5935 MHz in Denmark, and besides, there are more on-going implementation projects in Europe (and also outside of Europe, e.g. in China) by Finland, France, Spain and Sweden. Namely, in the last version of ETSI TR 103 667 (under preparation) [48], the spectrum sharing options in the context of the new CEPT band plan for 5.9 GHz are being discussed, considering this extension of the band from 5925 MHz to 5935 MHz.

5.2.2 Co-channel coexistence between ITS-G5 and LTE-V2X technologies

In the last version of ETSI TR 103 766 (under preparation) [49], the feasibility of the co-channel coexistence between ITS-G5 and LTE-V2X access technologies is being assessed. When this coexistence is uncoordinated and both technologies exist in the same frequency channel without adaptation (i.e. without co-channel coexistence mechanism), the behaviour will be suboptimal for both technologies in one way or another, resulting in:

- Message collision: Messages on the different access technologies overlap in time, rendering either one or both messages invalid depending on the geographical position of the transmitting and receiving ITS stations, thus leading to loss of data.
- Imbalance in channel access: One technology does not (sufficiently) release the channel for the other technology, leading to access starvation for this other technology.

There are several co-channel coexistence methods between ITS-G5 and LTE-V2X, which enable both technologies to **use the same frequency channel in the same geographical area.** All methods are based on sharing the possible division of channel resources between the two technologies in the time domain, since ITS-G5 always uses the whole bandwidth for transmission (LTE-V2X can also divide resources in the frequency domain).

5.2.3 Sharing in the time domain

This technique is a classical time division multiplexing (TDM) approach with static division of time resources. Sharing in the time domain implies that the available time is divided into time slots, where one technology will occupy the whole bandwidth for a certain time slot. How the resources are used within each time slot interval is decided by the **medium access control scheduling** for each technology. On the one hand, ITS-G5 always uses the whole bandwidth of the channel (10 MHz) for every transmission, and depending on the payload, the packet transmission duration is variable. However, it cannot divide the channel resources in frequency. On the other hand, LTE-V2X has a fixed subframe of 1 ms and cannot vary the packet length, but it can further divide this into the frequency domain as depicted in Figure 29.

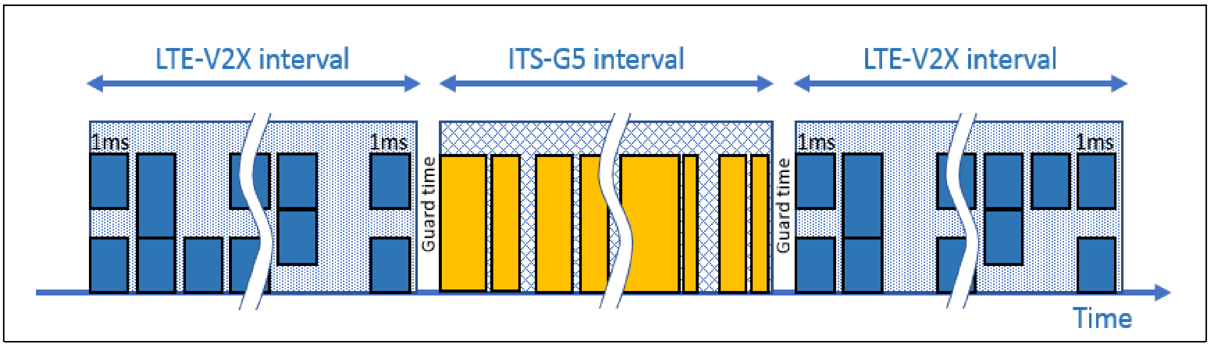

Figure 29: Example of how ITS-G5 and LTE-V2X technologies share frequency channel in the time domain

Due to inaccurate time synchronisation or the propagation delay, transmissions at the end of the reserved time for one of the systems can generate interference at the start of the time reserved for the other system. For this reason, there may be a guard time when transitioning from one technology time slot to another so as to avoid interference between both systems.

5.2.3.1. Deterministic timing

The available time resources of a channel are fairly shared between ITS-G5 and LTE-V2X, depending on the relative traffic load, which is observed in a given geographic location and at a given time. The division of channel resources between ITS-G5 and LTE-V2X is based on a distributed mechanism which decides on the deterministic start time, end time and duration of the ITS-G5 and LTE-V2X transmission intervals (i.e. no centralized control entity is required to coordinate between the systems).

5.2.3.2. Orthogonality of channel access

Both systems will limit any channel access to their respective ITS-G5 and LTE-V2X transmission intervals. To ensure a **non-interfering operation** of distinct radio communications technologies, orthogonality between corresponding transmissions is required.

As mentioned above, ITS-G5 uses the whole bandwidth of the channel and cannot divide the channel resources in frequency, whereas LTE-V2X cannot vary the packet length in the time domain but instead in the frequency domain. Thus, the orthogonality needs to be performed in the time domain.

In the last version of ETSI TR 103 667 (under preparation) [49], an overall framework for **spectrum sharing** between ITS-G5 and LTE-V2X technologies is presented, enabling both technologies to **use the same spectrum in the same geographical area.** This can be adapted to specific deployment scenarios based on the **priorities assigned to each technology in each of the channels.** Besides, since this approach aims at coexistence between two technologies with different radio air interfaces, it is challenging to provide a reliable solution without impacting the PHY/MAC structure of the involved technologies. Hence, the proposed approach can be formalised as follows:

- Each channel has an assigned priority to each technology.
- Based on the selected channels and the assigned priorities, one of the following actions can be taken in the case that one technology detects the other technology:

- VACATE: Device from a technology should vacate/change to another channel when the other technology is detected.
- STAY: Device from a technology should stay on the current channel when the other technology is detected.
- SHARE: In this case, the channel should be shared with one of the coexistence methods defined in ETSI TR 103 766 (under preparation) [50], as explained in the previous paragraphs.

5.2.4 Other co-channel coexistence methods proposed in the literature

In ETSI TR 103 580 [50], different methods are presented so as to ensure co-channel coexistence in the frequency range 5915 MHz to 5925 MHz, where urban rail is the priority application. Only the interference effects of active road ITS devices in the vicinity of an urban rail communication system in the designated urban rail channels are identified, discarding the identification of the interference effects of urban rail on road ITS channels. Therefore, no specific sharing methods for the operation of urban rail equipment in the road ITS bands are considered.

The sharing techniques described in the present document are also applicable to other frequency bands:

1. Methods to define protected zones: A measurement campaign will be needed to validate these results and to confirm the simulation parameters, which should be used to define the proper mitigation area to protect urban rail communications.
2. Protected zone detection methods: The solutions proposed are based on MAC/PHY layer, considering additional requirements such as regulatory, operational and installation aspects. The choice of the final one is still to be done among the following:
    - Read-only database combined with alert beacons.
    - Updatable database combined with optional permissive beacons.
3. Mitigation techniques to apply in protected zones: They are based on the implementation of an **adjustment of road ITS EIRP** (Equivalent Isotropic Radiated Power), as a progressive reduction with several steps when approaching the urban rail line, up to stop transmission on urban rail channels. Note that ETSI EN 302 571 [51] specifies the radio frequency parameters expected for the operation in the frequency range 5855 MHz to 5925 MHz, such as the carrier centre frequencies, the maximum output power, the maximum power spectral density, the transmitter unwanted emission limits in the out-of-band domain of the 5 GHz ITS frequency band, the receiver selectivity, the receiver sensitivity, among others.

Finally, ETSI TR 103 562 [52] presents the specification of the Collective Perception Service (CPS) to support applications in the domain of road and traffic safety applications. In principle, it was designed for the automotive sector, but it could be also extrapolated to urban rail ITS running on tracks along public streets such as tramways.

The CPS aims at enabling Intelligent Transport Systems-Stations (ITS-S) to share information about other road users and obstacles that were detected by local perception sensors such as radars, cameras and alike. In that sense, it aims at increasing awareness between ITS-Ss about the dynamic road environment in a cooperative manner, by mutually contributing information about their perceived objects. The service does not differentiate between detecting connected or non-connected road users.

This includes the specification of the Collective Perception Message (CPM), which allows the sharing of information about detected objects by the ITS-Ss. The message consists of information about the ITS-S itself, its sensory capabilities and its detected objects (position, speed, heading, classification, etc.). The CPM is transmitted cyclically with adaptive message generation rates to decrease the resulting channel load, thus minimizing channel utilization. In some situations, it can be meaningful to also include information obtained from received CAM (Cooperative Awareness Message) messages. Applications using aggregated CAM information are typically relevant for services provided by the infrastructure side and the ITS central systems.

5.2.5 Spectrum for FRMCS

This ECC Decision addresses the designation of the **paired frequency bands 874.4-880.0 MHz and 919.4-925.0 MHz** and of the **unpaired frequency band 1900-1910 MHz** to be used for Railway Mobile Radio (RMR) harmonized communications. RMR encompasses GSM-R and its successor(s), including the Future Railway Mobile Communication System (FRMCS) [54].

This band is exclusive for railway applications.

Currently the shared band between road ITS and urban rail-ITS is the 5.9 GHz using the ITS-G5 technology. This technology can be hybridised with cellular systems such as LTE and future 5G NR technology. Standardisation already relying in alternative 4G systems, LTE-V2X or C-V2X (Cellular-V2X) already exists. 5G technology will also allow V2X communication with Release 16. However, in the context of bearer flexibility already assured by FRMCS with multi radio access technologies (Wi-Fi, LTE, 5G and satellite), it is interesting to analyse the possibility of coexistence and synergies between road and rail systems.

As in the case with the interference between GSM-R and other public networks [54], the interference between FRMCS and other public networks could increase since both railway and public operators aim to have good coverage along the rail tracks. Instead of cooperating in network planning, railway and public operators “fight for” the coverage. The interference could result in severe impairment of voice and data communications, as well as network loss over several hundred meters of track.

The services that could rely on a shared infrastructure must be evaluated in order to verify that safety/security is not affected.

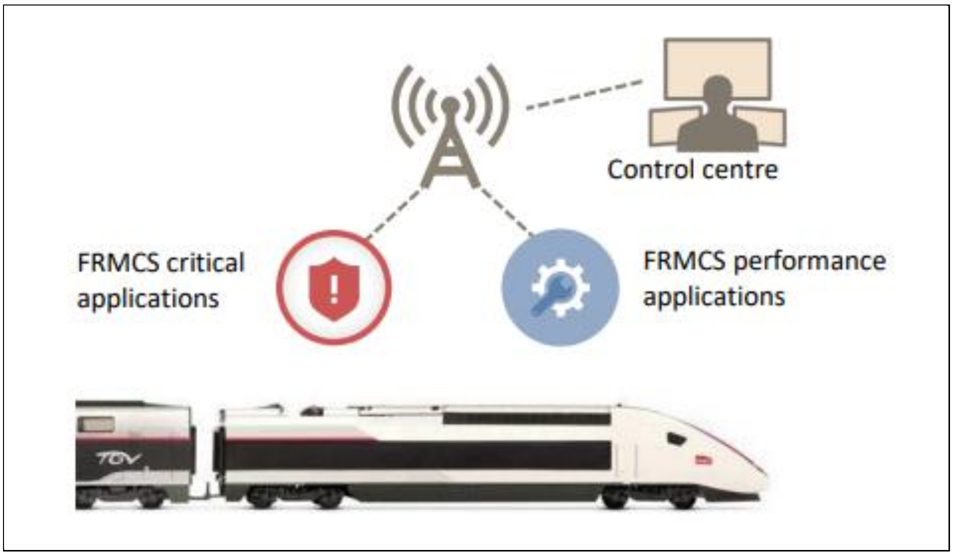

Figure 30: FRMCS critical and performances applications [12]

5.3. The case of the Backhaul and core network

Coexistence of road and railway services and data traffic will not only be affected by radio spectrum co-use, and the related likely radio interference and considerations for differentiated or shared radio Access Network. Data traffic from the differentiated services for road and traffic may eventually converge into tunnelling backhaul and core networks. It is in these networks where the components of the data traffic mix may need to be differentiated, in order to provide the corresponding Quality of Service (QoS) and differentiated routing that the associated road and railway services will demand.

A traditional way of dealing with this traffic differentiation is the use of “virtual networks”. Virtual networks are a logical construction, usually implemented thanks to the application of traffic tagging techniques [55]. Labelling the packets with a specific, pre-agreed tag, allows for the traffic elements to apply different operations to the data packets based on those tags: enqueuing in priority queues, routing through specific paths, and so on. While tagging and virtual networks have been used for decades, the concept has experienced a “revival” in the last years as underlying methodology enabling the so-called “network slicing” [56], [57]. Slicing refers to the split of network traffic and resources, based on some specific consideration, such as user (tenant) or service. For example, in the context of this deliverable, a network or its component subnetworks (radio access/backhaul/core) could be split into a slice for road data traffic and another for railway data traffic. Besides, within those domain specific slices, additional slices could be defined per service. From a networking perspective, these “slices” are just mere “virtual networks” where the isolation is just logical, based on tagging. Another example is illustrated in the following figure, where data traffic related to FRMCS and other digital rail services is split into different slices (illustrated by colour) within a 5G Network and treated accordingly: routing it to different networks and providing the necessary QoS mechanisms, until reaching the ultimate servers. Note that this “colour codes” could be implemented as different “tags” into the corresponding packets, when entering the network.

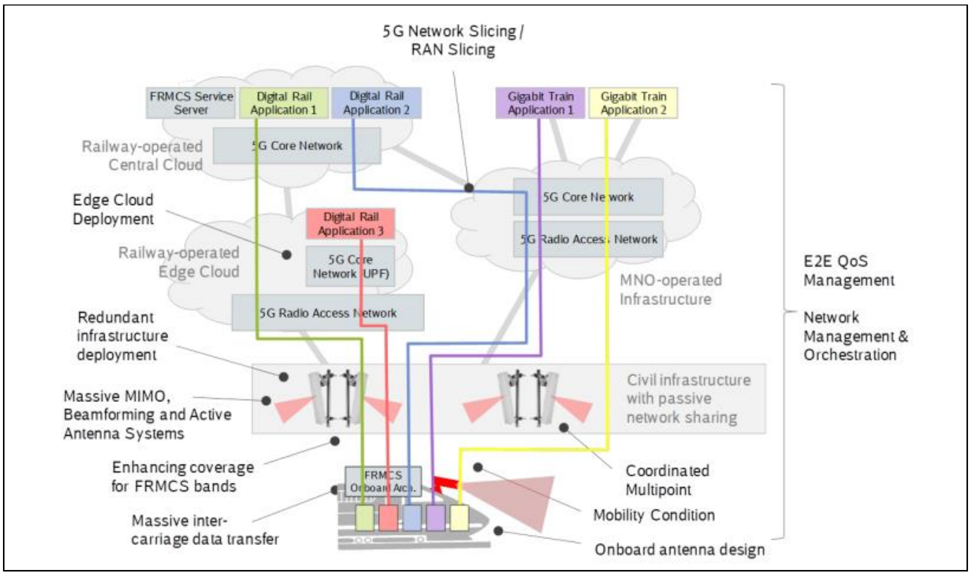

Figure 31: FRMCS in 5G Network Slicing / RAN Slicing [59]

The possibility of defining "slices" over the network traffic and its components extends beyond the mere "logical" separation, as a real, physical, network segmentation can be built to accommodate the specific slices. As a result, it is possible to define multiple actors in the management of the network and stage-delegate responsibilities accordingly. As illustrated in the next figure, and in the context of railway, this allows splitting the responsibility for the service provision among an infrastructure manager (IM) and one (or multiple) mobile network operators (MNO), with different grades of operation.

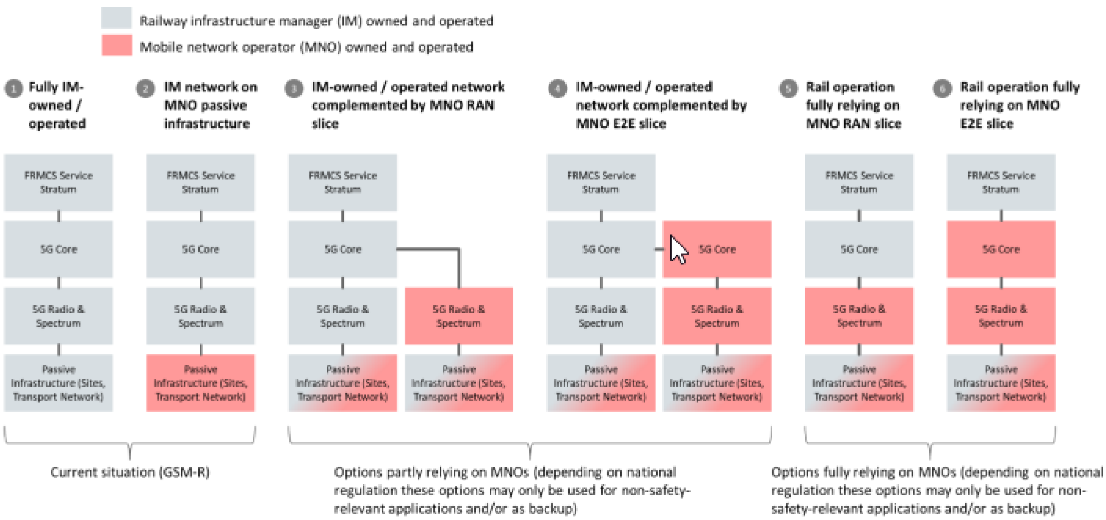

Figure 32: Principal deployment options for Digital Rail Operations [59]

6 METHODOLOGY AND DEFINITION OF COEXISTENCE SCENARIOS

In alignment with the scope of the Deliverable, and based on the previous background provided for the state and mechanisms for each of the domains, infrastructure and specific services, this section proposes a methodology for definition of coexistence scenarios between road and railway, from the point of view of telecommunication infrastructure.

The methodology is based on splitting the different likely elements that compounds the service provision as represented in the following graph in Figure 33.

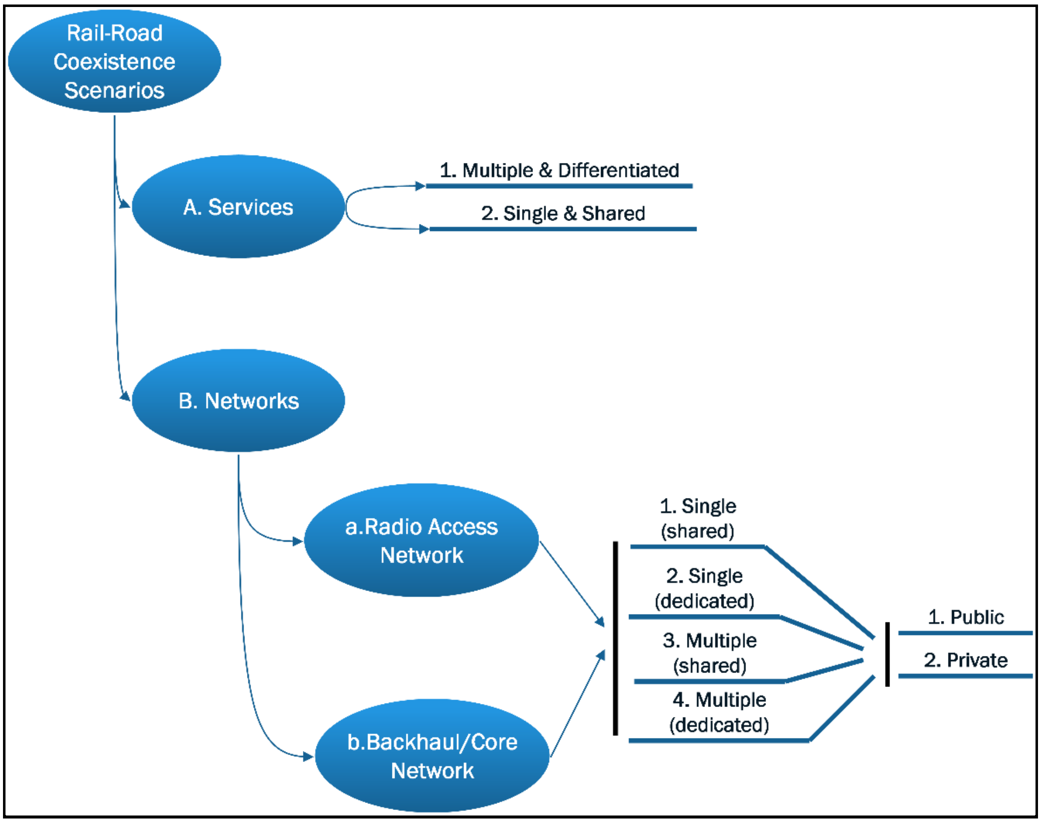

Figure 33: Illustration of the methodology chosen for the identification of the scenarios

This classification can be used as a tool to define scenarios from the point of view of telecommunication infrastructure, for example:

- A scenario with A.1 (multiple and differentiated services for Rail and Road) and B.a.1.1 (a single shared and public Radio Access Network, for example 5G by a commercial operator) and B.b.4.2 (multiple dedicated private core networks for rail and road traffic).
- A scenario with A.1 (multiple and differentiated services for Rail and Road) and B.a.4.2 (multiple dedicated private radio access networks for rail and road traffic) and B.b.1.1 (a single public core network, for example by a commercial operator/carrier).

For the definition of this scenario-taxonomy generator, the main variables are:

- The amount of Radio Access Technologies (RATs) and associated Radio Access Networks (RANs), which provide bearer flexibility, and whether these RANs are shared (e.g. a common 5G access for rail and road) or dedicated (e.g. 5G for regional rail, 4G for road, Wi-Fi for urban railway). An additional variable allows differentiating these RANs as public (other services and traffic profiles simultaneously) or private. From this perspective, having differentiated RANs would limit the coexistence scenario to interference issues between the different RATs. Having a common RAN would eliminate interference issues in a coexistence scenario, and limit the coexistence scenarios to traffic differentiation and management in the common RAN.
- The amount of core networks, which may determine the mechanisms for traffic differentiation and management (QoS provision and guaranties), e.g. slicing, SDN operation, domain coordination, etc. The fact that these networks are public or private will also have implications for the coexistence scenarios.

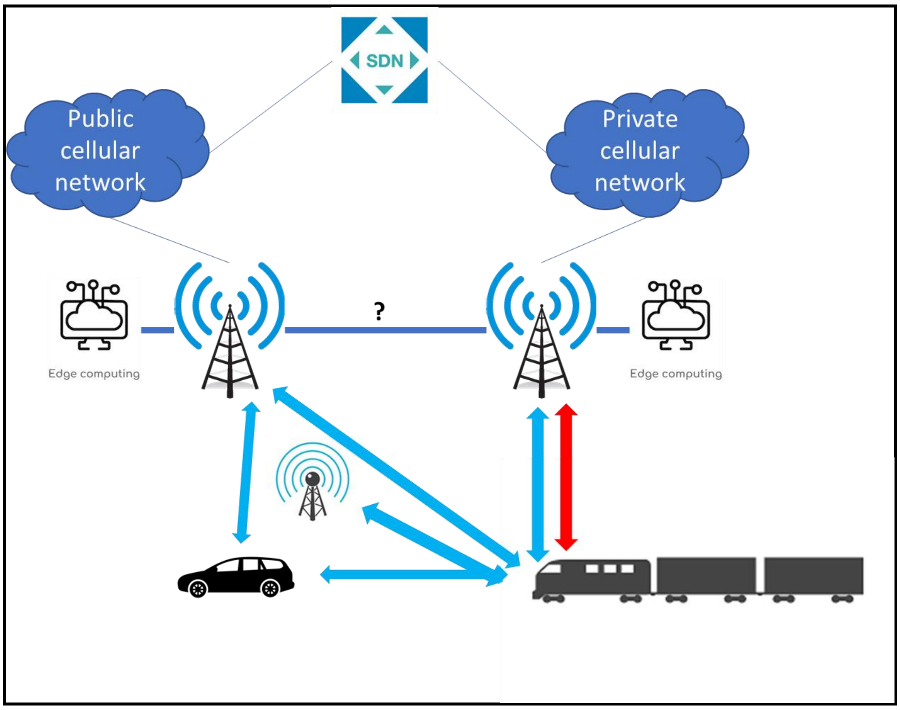

Figure 34: Case with B.a.4.2 and B.a.4.1 from the point of view of Radio Access and B.b.4.1 and B.b.4.2 from the point of view of Core)

With this methodology, a complete taxonomy of cases and scenarios could be defined.

Additional variables could be added as well to the methodology (e.g. differentiated users for each specific domain (e.g. cargo vs commercial railway consists). This would make the cases definition richer, but would not add substantial differential ground from a telecommunication perspective. Therefore, no more variables are included in the methodology, but this does not preclude to include additional variables in the definition of specific scenarios.

In the following, it is assumed that no common service for both domains will exist in the near or mid-term future, except from emergency broadcast – notifications. Therefore, the considered cases will be based on component A.1 as per Figure 33.

For the purpose of this deliverable, and to infer a number of likely coexistence scenarios, the following considerations have been made:

1. In relation to Access and Core Networks, the Backhaul is considered, for simplification, a part of the Core Network. Besides, only a differentiation between shared or dedicated network has been made, assuming that any public network is a shared network and any private network is a dedicated network. Even though there can be cases where a private network is shared by several stakeholder's traffic, the cases have been reduced to these two for simplification purposes. Likewise, for the Radio Access Network, two different cases are observed, that there is a single technology (e.g. only 5G, or only Wi-Fi), or that different technologies coexist (e.g. Wi-Fi and 5G and other). Based on this, the following combinations, as illustrated in Table 9, have been considered:

Table 9: Considered combination cases for Radio Access and Core Network

		Dedicated	Shared
Radio Access Network	**Single Techno**	R1	R2
	Multiple Techno	R3	R4
Core Network		C1	C2

Table 9 allows combining the different Radio Access and Core Network options in order to derive Cases from the point of view of these Telecommunication infrastructure elements, as illustrated in Figure 35.

Telco Cases

T1 R1C1: There is a single technology in the access network, although each domain has its own dedicated RAN and its own dedicated core network.
T2 R1C2: There is a single technology in the access network, although each domain has its own dedicated RAN and both share the core network.
T3 R2C1: There is a single technology in the access network, the RAN is shared but each domain has its own dedicated core network.
T4 R2C2: There is a single technology in the access network, the RAN is shared, and both share also the core network.
T5 R3C1: There are different technologies in the access network, each domain has its own dedicated RAN and its own dedicated core network.
T6 R3C2: There are different technologies in the access network, each domain has its own dedicated RAN and both share the core network.
T7 R4C1: There are different technologies in the access network, the RAN is shared, but eac hdomain has its own dedicated core network.
T8 R4C2: There are different technologies in the access network, the RAN is shared as well as the core network.

Figure 35: Cases from the point of view of telecommunication infrastructures

2. In relation to types of Railway and Road, the types outlined in Section 2.1 have been, for simplification purposes, reduced to those illustrated in Table 10, where:

- The regional train type englobes the Main Line and Regional Line cases in Section 2.1.
- A new Tram type has been added to differentiate it from Urban/Suburban as per Section 2.1.
- Urban and Rural roads as per Section 2.1 has been merged in a single type (Road).

Table 10: Types of considered infrastructure to derive combination cases

	Tram	Urban Train	Regional Train	High Speed Train
Highway	M1	M2	M3	M4
Road	M5	M6	M7	M8

By combining these different types of rail and road infrastructure, 8 different cases -so called “Mobility cases”- could be inferred, as illustrated in Figure 36:

Mobility Cases	
M1	Highway and Tram.
M2	Highway and Urban Train.
M3	Highway and Regional Train.
M4	Highaw and High Speed Train.
M5	Road and Tram.
M6	Road and Urban Train.
M7	Road and Regional Train.
M8	Road and High Speed Train.

Figure 36: Inferred cases from the combination of different mobility types

3. In relation to types of infrastructure and their topological setup, the considered variables from those illustrated in Section 2 were the following:

- Whether the rail tracks where parallel or perpendicular to the road lanes.
- Whether they were on the open (or bridge) or in a tunnel.
- Whether they were on the same vertical plane or not.

As a result, of combining these topological variables, the cases illustrated in Figure 37 were obtained:

Topology Cases	
P1	Track paralell to road, open air/bridge, same plane.
P2	Track paralell to road, open air/bridge, different planes.
P3	Track Parallel to road, tunnel, same plane.
P4	Track perpendicular to road, open air, same plane (level crossing).
P5	Track perpendicular to road, open air, different planes.
P6	Track perpendicular to road, tunel, different planes.

Figure 37: Infrastructure topological setup considered cases.

With the obtained 8 cases from the Telecommunication Infrastructure point of view, together with the 8 Mobility Cases and 6 Topological cases, it was possible then to define Coexistence Scenarios, where all the possible variable combinations can be used in a systematic way. The total amount of coexistence scenarios that can be defined following this methodology are 384, which can be represented as in the example Table 11:

Table 11: Partial representation of Coexistence Scenarios, based on derived cases

T1	M1	P1	SCENARIO111
		P2	S112
		P3	S113
		P4	S114
		P5	S115
		P6	S116
	M2	P1	S121
		P2	S122
		P3	S123
		P4	S124
		P5	S125
		P6	S126
	M3	P1	S131

Table 11 illustrates how all the 384 coexistence scenarios can be derived and named based on the combination of the presented cases. The chosen nomenclature for the scenarios is representative of the combinatory case chosen, so that this is implicit in the scenario name. For example, Scenario 123 refers to the combinatory case where:

1. T1: There is a single technology in the access network, although each domain has its own dedicated RAN and its own dedicated core network.
2. M2: The type of mobility case considered is the one for Highway and Urban Train.
3. P3: The topological case is the one for railways tracks parallel to road lanes, in a tunnel, on the same vertical plane.

It is already clear that describing the whole casuistic and possibilities for coexistence scenarios, 384 in total, and after simplifying some of the grounding variables, can be overwhelming. Therefore, only some significant scenarios will be described in the following section, as exemplary coexistence scenarios for railway and road.

7 DESCRIPTION OF COEXISTENCE SCENARIOS EXAMPLES

7.1 Introduction

As per the coexistence scenario discrimination presented in the previous section, a few examples of scenarios are being described in the following to provide completeness to the scenario definition. As mentioned, 384 likely scenarios can be defined following the presented methodology, therefore only a few representative ones are described fully in this section, providing a methodological template to define others when necessary.

7.2 Scenario 151

Scenario 151 refers to the case combination in which:

1. In relation to Telecommunication infrastructure, there is a single technology in the access network (for example 5G), although each domain has its own dedicated radio access network and its own dedicated core network.

5. In relation to the mobility cases, this scenario refers to the case of coexistence of Road car traffic and Tram.

1. The scenario deals with the topological case where Railway tracks are parallel to Road lanes in the open air and on the same plane.

This is illustrated in Figure 38.

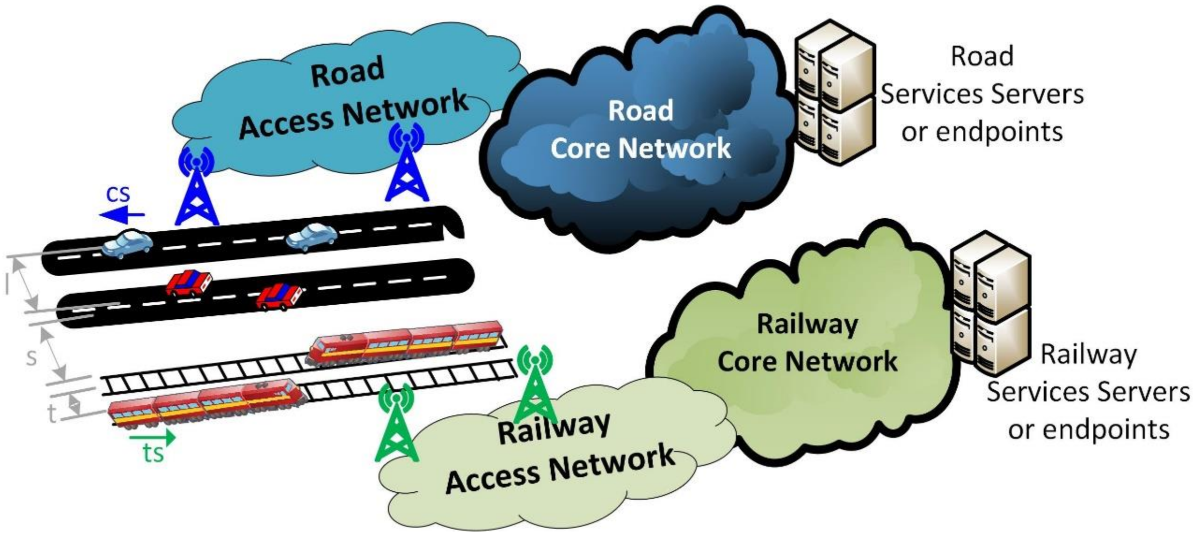

Figure 38: Scenario 151

7.2.1 Topology and Mobility Cases

Scenario 151 deals with Mobility Case 5, where Road car traffic and Tram are considered, together with Topology Case 1, where road lanes and railway tracks run parallel to each other. This is translated into the following parameters:

- Number of road lanes per direction: 2.
- Number of railway tracks: 2.
- Separation between directional road lanes (l): 0,5m.
- Separation between railway tracks (t): 2m.
- Separation between road lanes and railway tracks (s): 4 m.
- Maximum cars speed (cs): 50 km/h (general speed limit for urban roads in EU Member States).
- Maximum trams speed (ts): 50 km/h.
- Cars traffic flow (per direction): 3200 vehicles/hour (dense traffic flow, very short distance among vehicles).
- Tram frequency: 16 trains/hour.
- Tram composition: a minimum of 4 cars (2 motor cars and 2 trailer cars).
- In principle, any type of motorized road vehicle that may equip on-board communication devices is considered, thus discarding motorbikes, as well as VRUs (pedestrians, bicycles…).

Optional features that may be considered in this scenario:

- Two parallel trams running among a considerable number of road vehicles.
- The distance covered is 2 km in opposite direction, considering a crossing of trams in a certain point of the city.
- Sections of single and 2 road lanes are combined (it is dependent on the layout of the city itself: avenues, downtown…).
- Many traffic lights and traffic signs can be considered in such a dense urban environment.
- These trams can be driven manually (presence of a driver in the cabin) or remotely (from an operation centre).
- These trams can also be driverless autonomous/automated trams. Different grades of automation (GoA) can be considered.
- Likewise, road vehicles can be driven manually, remotely or autonomously. For the latter case, different levels of automation can be considered.
- A platooning of road vehicles in front of one of the trams may be considered.
- This urban area is surrounded by high or medium size buildings (depending on the street covered by the tram at any given time).

7.2.2 Telecommunication infrastructure case

Scenario 151 deals with Case 1, in which there is a single technology in the access network (for example 5G), although each domain has its own dedicated radio access network and its own dedicated core network. This implies that:

a) Radio Access Technology: The same technology will be shared between rail and road services (5G radio is assumed). In this case, issues related to interference within the same technology should be considered, as illustrated in Section 5.2.

b) Radio Access Network: despite having a common technological base, two dedicated and independent radio access networks exist for each domain (i.e. one RAN for rail services and the other one for road services). Based on this, the access points to the network (gNBs for the case of 5G) will not be shared, as illustrated in Figure 39. This implies that the different data flows associated to the services/Applications in each domain will not share radio access network resources (although issues related to (a) may have an impact). Therefore, both rail and road services will compete to have a good coverage instead of cooperating in network planning, which is why the coexistence mechanisms shall be focused on guaranteeing the performance of these independent networks without interference.

c) Core Network: likewise, this scenario assumes that each domain will have its own core network, independently of each other, serving their associated services and applications. As a result, data-traffic management and optimization is planned and carried out independently for the two domains. However, this does not preclude the possibility, within each of these domain networks, to apply the techniques described in Section 5.3 to achieve application/service data traffic discrimination: virtual networking principles and associated QoS techniques could be applied to guaranty QoS and assure KPIs for each of the domains.

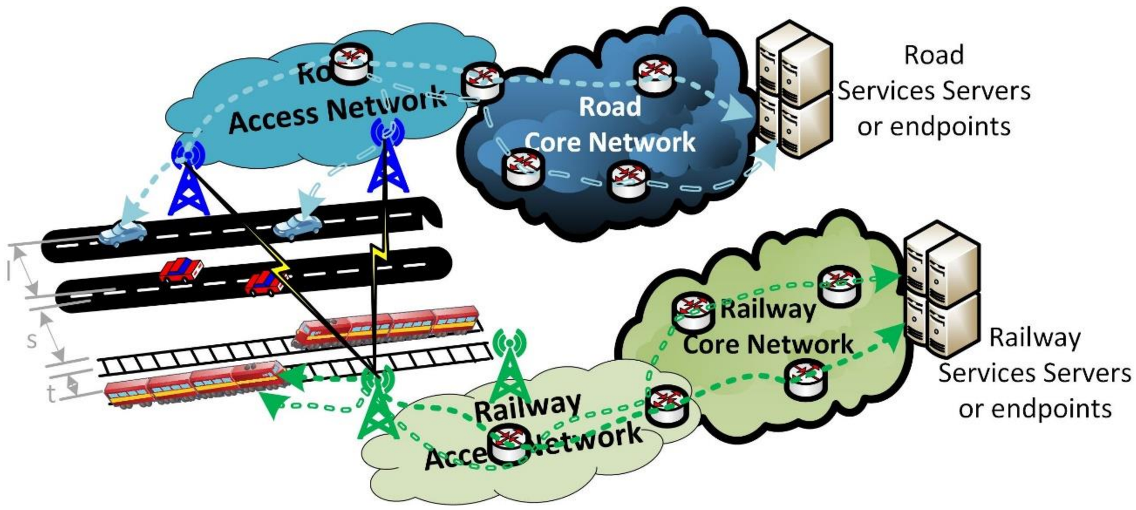

Figure 39: Example of data traffic in Coexistence Scenario 151

As illustrated in Figure 39, the implications for data flows in this coexistence scenario is that, besides the radio channel likely interferences, the data flows associated to the application/services in each domain do not coexist at network level and they are by default discriminated thanks to the network differentiation both at access and core network levels.

In terms of radio communication equipment, a single transmitter/receiver is considered for cars, while two radio units are considered for trains.

Typical applications/services are described in Section 4 with details of the corresponding traffic characterization, and the mapping between these traffic types and those considered in other WPs of the project is provided.

7.3 Scenario 181

Scenario 181 refers to the case combination in which:

1. In relation to Telecommunication infrastructure, there is a single technology in the access network (for example 5G), although each domain has its own dedicated radio access network and its own dedicated core network.

8. In relation to the mobility cases, this scenario refers to the case of coexistence of Road car traffic and High Speed train traffic.

1. The scenario deals with the topological case where Railway tracks are parallel to Road lanes in the open air and on the same plane.

This is illustrated in the following figure:

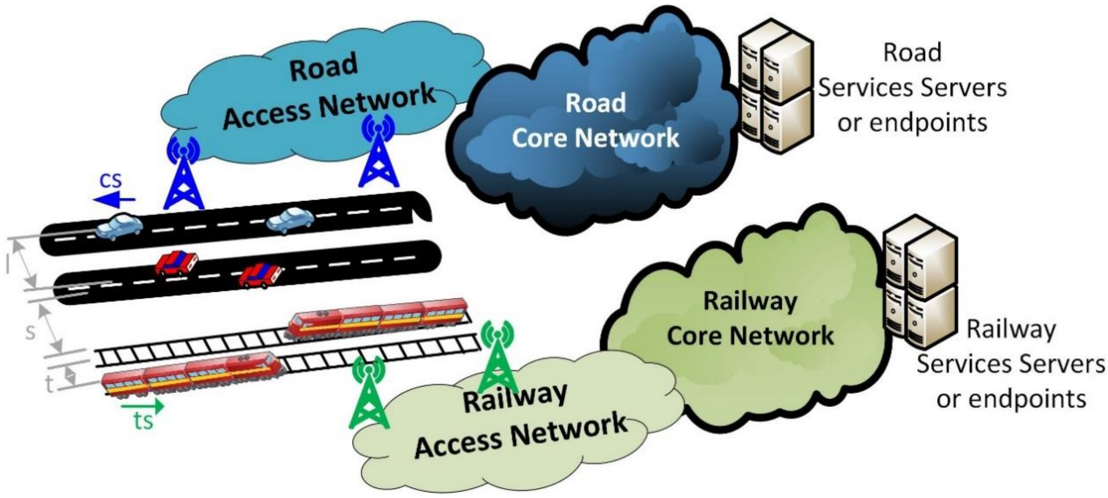

Figure 40: Scenario 181

7.3.1 Topology and Mobility Cases

The scenario deals with Mobility Case 8, where Road car traffic and High Speed railway traffic are considered, together with Topology Case 1 where road lanes and railway tracks run parallel to each other. This is translated into the following parameters:

- Number of road lanes per direction: 2.
- Separation between directional road lanes (l): 0,5m.
- Separation road lanes – railway tracks (s): 4 m.

- Separation between railway tracks: 2m.
- Max speed cars (cs): 80 km/h.
- Max speed trains (ts): 200 km/h.
- Cars traffic flow (per direction): 3200 vehicles/hour.
- Train frequency: 16 trains /hour.

7.3.2 Telecommunication Infrastructure Case

Scenario 181, deals with case 1 in which there is a single technology in the access network (for example 5G), although each domain has its own dedicated radio access network and its own dedicated core network. This implies that:

a) Radio Access Technology: (5G radio is assumed). Issues related to interference within the same technology should be considered, as illustrated in Section 5.2.
b) Radio Access Network: despite having a common technological base, different, dedicated, radio access networks exist for each domain. Based on this, the access points to the network (gNBs for the case of 5G) will not be shared, as illustrated in Figure 40. This implies that the different data flows, associated to the services/Applications in each domain will not share radio access network resources (although issues related to (a) may have an impact.
c) Core Network: likewise, this scenario assumes that each domain will have its own core network, independently of each other, serving their associated services and applications. As a result, data-traffic management and optimization is planned and carried out independently for the two domains. This does not preclude though the possibility, within each of these domain networks, to apply the techniques described in Section 5.3 to achieve application/service data traffic discrimination: virtual networking principles and associated QoS techniques could be applied to guaranty QoS and assure KPIs for each of the domains.

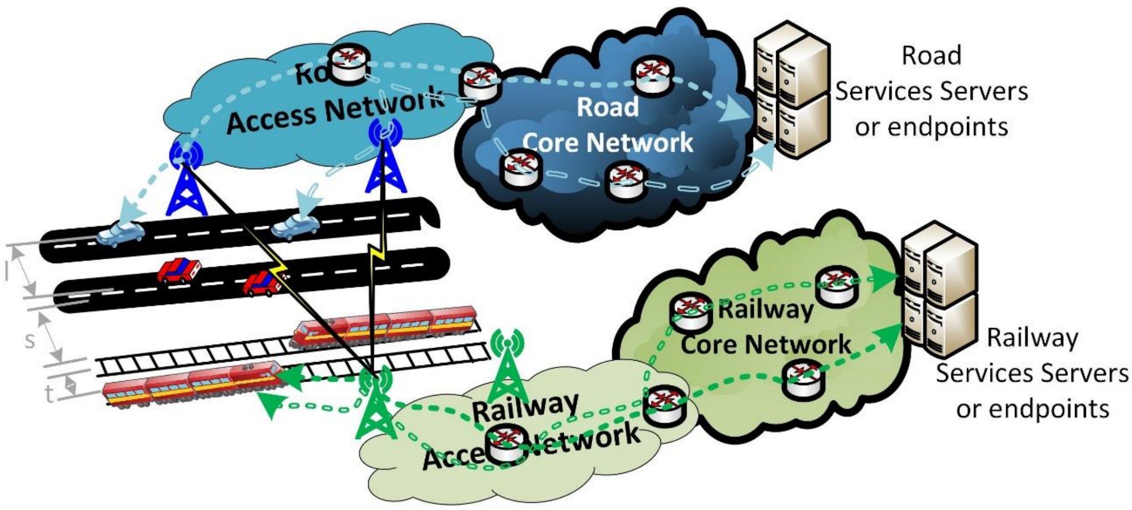

Figure 41: Example of data traffic in Coexistence Scenario 181

As illustrated in Figure 40, the implications for data flows in this coexistence scenario is that, besides the radio channel likely interferences, the data flows associate to the application/services in each domain do not coexist at network level and they are by default discriminated thanks to the topological network differentiation both at access and core network levels.

In terms of transmission equipment, a single transmitter/receiver is considered for cars, while two are considered for trains.

Typical applications/services are described in Section 4 with details of the corresponding traffic characterization, and a mapping between these traffic types and those considered in other WPs of the project is provided.

7.4 Scenario 451

Scenario 451 refers to the case combination in which:

4. In relation to Telecommunication infrastructure, there is a single technology in the access network (for example 5G) and both RAN and core network are shared by the different domains.

5. In relation to the mobility cases, this scenario refers to the case of coexistence of Road car traffic and Tram traffic.

1. The scenario deals with the topological case where Railway tracks are parallel to Road lanes in the open air and on the same plane.

This is illustrated in the following figure:

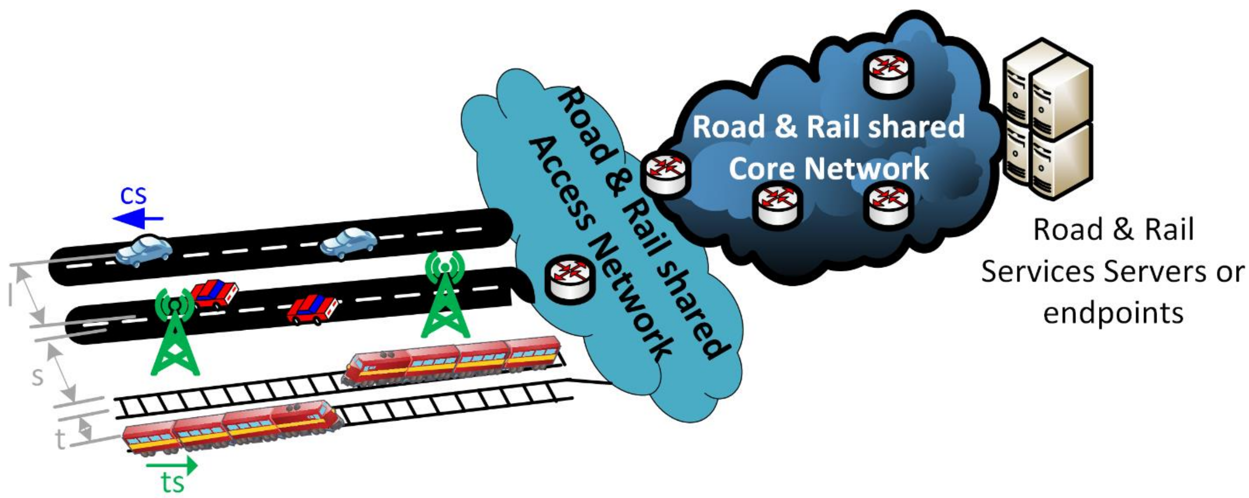

Figure 42: Scenario 451

7.4.1 Topology and Mobility Cases

The scenario deals with Mobility Case 5, where Road car traffic and Tram traffic are considered, together with Topology Case 1 where road lanes and railway tracks run parallel to each other. This is translated into the following parameters:

- Number of road lanes per direction: 2
- Separation between directional road lanes (l): 0,5m.
- Separation road lanes – railway tracks (s): 4 m.
- Separation between railway tracks: 2m.
- Max speed cars (cs): 30-50 km/h
- Max speed trains (ts): 30-50 km/h
- Cars traffic flow (per direction): 3200 vehicles/hour
- Tram frequency: 10 trams /hour.

7.4.2 Telecommunication infrastructure case

Scenario 451, deals with case 1 in which there is a single technology in the access network (for example 5G).

a) Radio Access Technology: (5G radio is assumed). Issues related to interference within the same technology should be considered, as illustrated in Section 5.2
b) Radio Access Network: a single, common, radio access network is considered for both domains. Thus, the access points to the network (gNBs for the case of 5G) will be shared, as illustrated in Figure 43. This implies that the different data flows, associated to the services/Applications in each domain will share radio access network resources. Issues related to RAN resources sharing should be considered.
c) Core Network: likewise, this scenario assumes that a single, common, core network is shared between the different domains, serving their associated services and applications. As a result, data-traffic management and optimization should be planned and carried out jointly for both domains. In this context, the techniques described in Section 5.3 should be applied to achieve application/service data traffic discrimination: virtual networking principles and associated QoS techniques could be applied to guaranty QoS and assure KPIs for each of the domains.

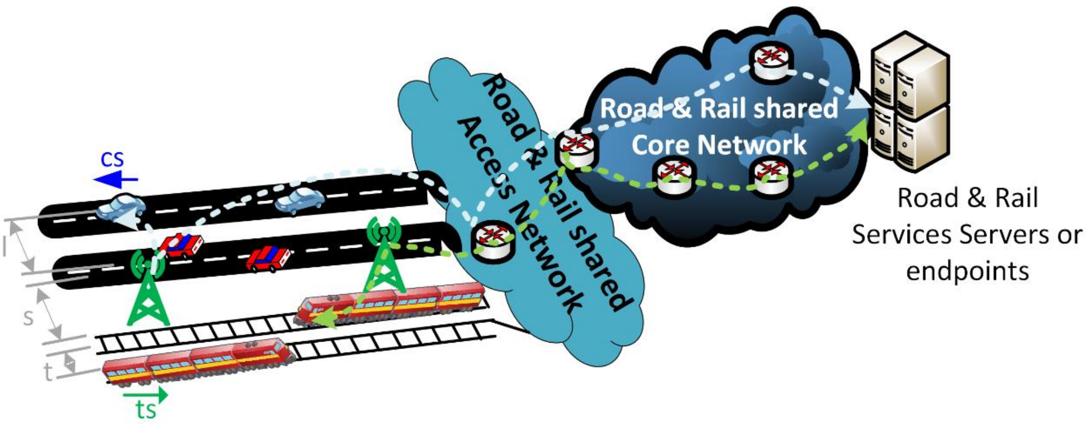

Figure 43: Example of data traffic in Coexistence Scenario 451

As illustrated in Figure 43, the implications for data flows in this coexistence scenario is that, besides the radio channel likely interferences, data flows associate to the application/services in each domain also coexist at access and core network levels. Traffic discrimination is therefore required to ensure an efficient coexistence.

In terms of transmission equipment, a single transmitter/receiver is considered for cars, while two are considered for trams.

Typical applications/services are described in Section 4 with details of the corresponding traffic characterization and with a mapping between these traffic types and those considered in other WPs of the project.

7.5 Scenario 473

Scenario 473 refers to the case combination in which:

4. In relation to Telecommunication infrastructure, there is a single technology in the access network (for example 5G), the RAN and the core network is shared.

7. In relation to the mobility cases, this scenario refers to the case of coexistence of Road Car Traffic and Regional Train traffic.

3. The scenario deals with the topological case where Railway tracks are parallel to Road lanes in tunnel and on the same plane (a physical wall separation exists between the rail and road).

This is illustrated in the following figure:

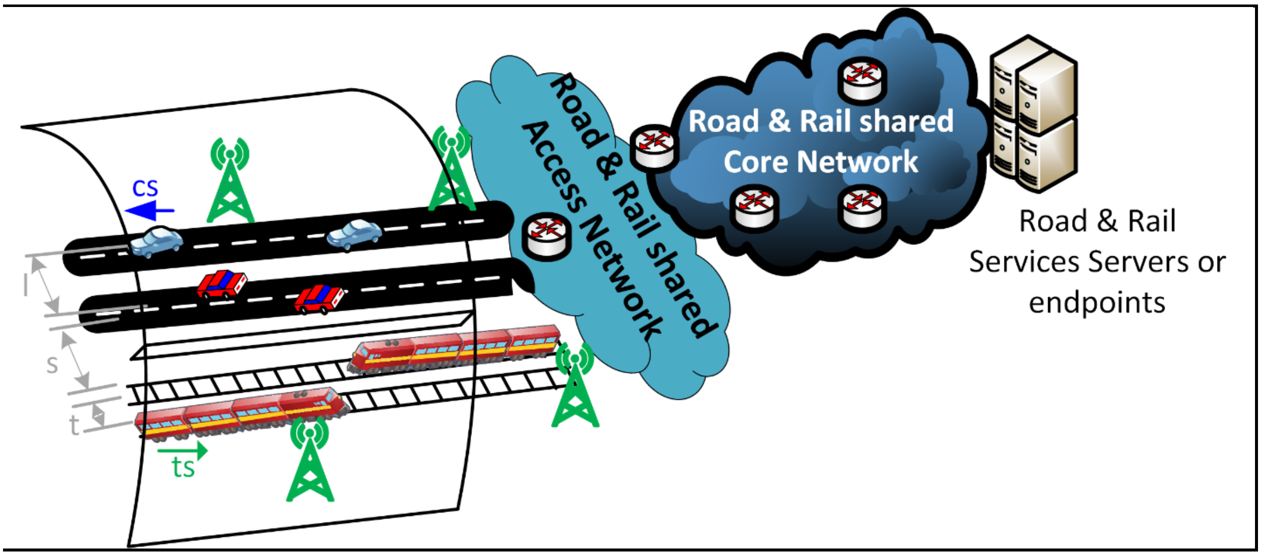

Figure 44: Scenario 473

7.5.1 Topology and Mobility Cases

The scenario deals with Mobility Case 7, where Road Car Traffic and Regional Train Railway Traffic are considered, together with Topology Case 3 where road lanes and railway tracks run parallel to each other in tunnel, with a physical wall separation between the rail and road. This is translated into the following parameters:

- Number of road lanes per direction: 2
- Separation between directional road lanes (l): 0,5m.
- Separation road lanes – railway tracks (s): 4 m.
- Separation between railway tracks (t): 2m.
- Max speed cars (cs): 80 km/h
- Max speed trains (ts): 200 km/h
- Cars traffic flow (per direction): 3200 vehicles/hour
- Train frequency: 16 trains /hour.

7.5.2 Telecommunication Infrastructure case

Scenario 473 deals with case 4 in which there is a single technology in the access network (for example 5G), the RAN and the core network is shared. This implies that:

a) Radio Access Technology: (5G radio is assumed). Issues related to interference within the same technology should be considered in the tunnel environment, as illustrated in Section 5.2.
b) Radio Access Network: a shared radio access network exists for both domains. Based on this, the access points to the network (gNBs for the case of 5G) could be shared or not, as illustrated

in Figure 45. This implies that the different data flows, associated to the services/Applications in each domain could share or not radio access network resources (issues related to (a) may have an impact).

c) Core Network: likewise, this scenario assumes that each domain will share the core network, serving their associated services and applications. As a result, data-traffic management and optimization is planned and carried out simultaneously for the two domains. The use of techniques as those described in Section 5.3 to achieve application/service data traffic discrimination could be applied to guaranty QoS and assure KPIs for each of the domains.

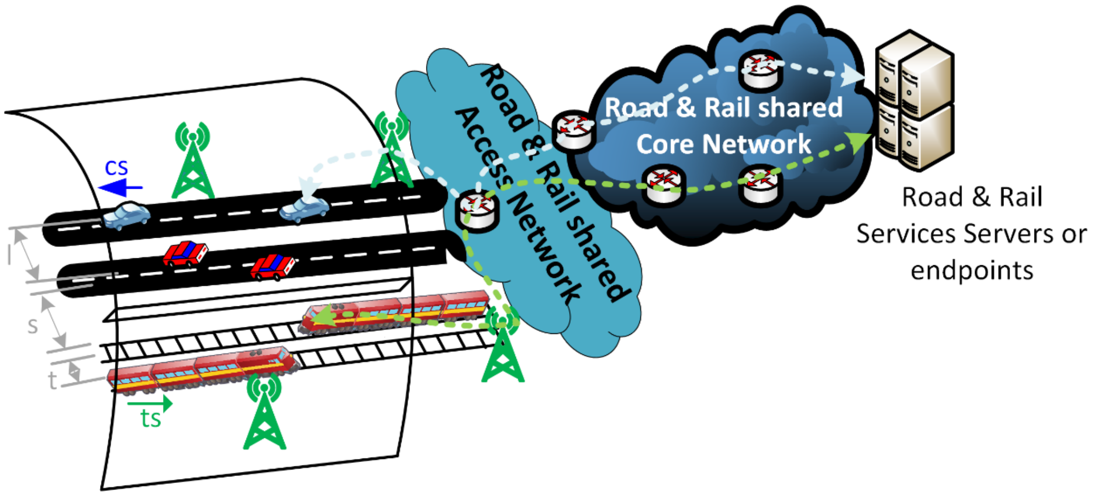

Figure 45: Example of data traffic in Coexistence Scenario 473

As illustrated in Figure 45, the implications for data flows in this coexistence scenario is that, besides the radio channel likely interferences, the data flows associated to the application/services in each domain coexist at network level and they are not discriminated because of network sharing for both at access and core network levels.

In terms of transmission equipment, a single transmitter/receiver is considered for cars, while two are considered for trains.

Typical applications/services are described in Section 4 with details of the corresponding traffic characterization. A mapping between these traffic types and those considered in other WPs of the project is also provided.

7.6 Scenario 674

Scenario 674 refers to the case combination in which:

6. In relation to Telecommunication infrastructure, there are different technologies in the access network (for example 4G, 5G and Wi-Fi), each domain has its own dedicated radio access network, and both share the core network.

7. In relation to the mobility cases, this scenario refers to the case of coexistence of Road car traffic and Regional train traffic.

4. The scenario deals with the topological case where Railway tracks are perpendicular to Road lanes in the open air and on the same plane (level crossing).

This is illustrated in the following figure:

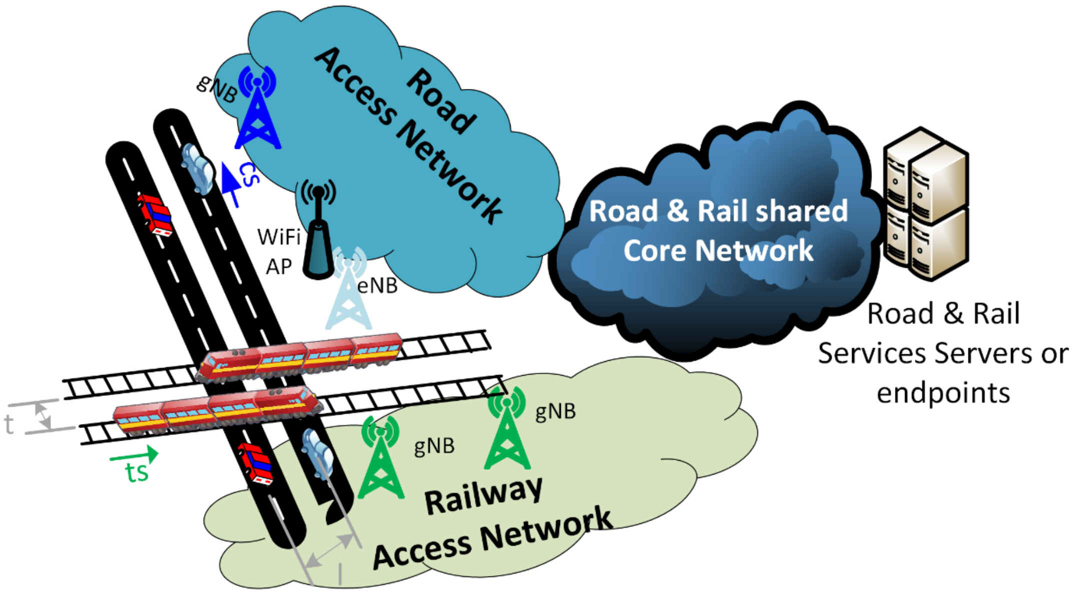

Figure 46: Scenario 674

7.6.1 Topology and Mobility Cases

The scenario deals with Mobility Case 7, where Road car traffic and Regional railway traffic are considered, together with Topology Case 4 where road lanes and railway tracks are perpendicular to each other. This is translated into the following parameters:

- Number of road lanes per direction: 1 or 2?
- Separation between directional road lanes (l): 0,5m.
- Number of railway tracks per direction: 1 or 2?
- Separation between railway tracks: 2m.
- Max speed cars (cs): 40 km/h
- Max speed trains (ts): 100 km/h
- Cars traffic flow (per direction): 200 vehicles/hour
- Train frequency: 4 trains /hour.

7.6.2 Telecommunication infrastructure case

Scenario 674 deals with the case in which there are different technologies in the access network (for example 4G, 5G and WiFi), each domain has its own dedicated radio access network, and both share the core network. This implies that:

a) Radio Access Technology: (4G and 5G radio is assumed). Issues related to interference within the same technology should be considered and also between different technologies, as illustrated in Section 5.2.
b) Radio Access Network: despite having a different technological base, dedicated, radio access networks exist for each domain. Based on this, the access points to the network (eNBs for the case of 4G, and gNBs for the case of 5G) will not be shared, as illustrated in Figure 47. This implies that the different data flows, associated to the services/Applications in each domain will not share radio access network resources (although issues related to (a) may have an impact).
c) Core Network: likewise, this scenario assumes that each domain will share the core network, serving their associated services and applications. As a result, data-traffic management and optimization is planned and carried out simultaneously for the two domains. Techniques as those described in Section 5.3 to achieve application/service data traffic discrimination could be applied to guaranty QoS and assure KPIs for each of the domains.

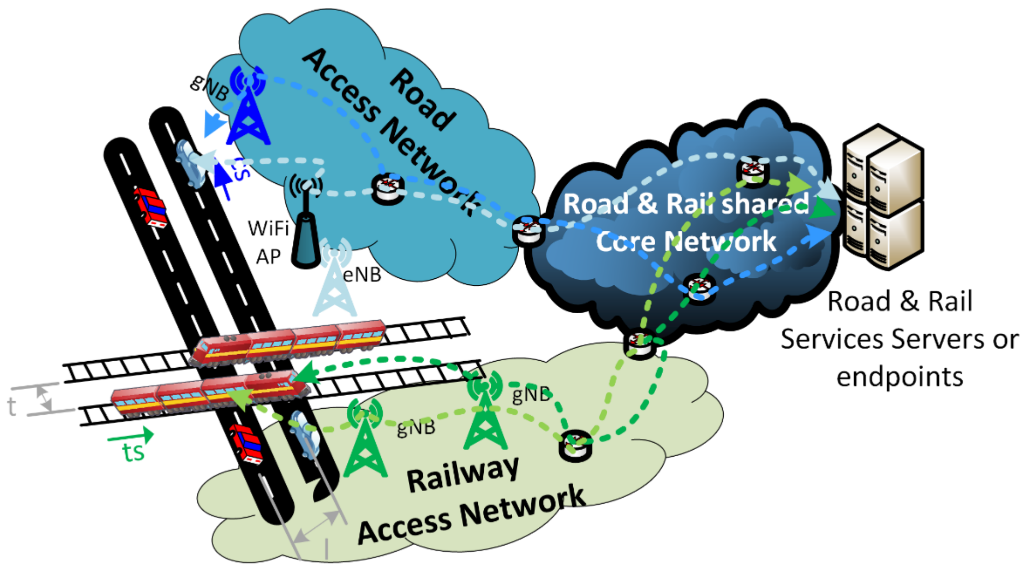

Figure 47: Example of data traffic in Coexistence Scenario 674

As illustrated in Figure 47, the implications for data flows in this coexistence scenario is that, besides the existing radio channel likely interferences and also between different technologies (4G, 5G, Wi-Fi), the data flows associated to the applications/services in each domain do not coexist at radio access level and they are discriminated, by default, due to different RAN topologies. Furthermore, the data flows associated to the application/services in each domain coexist at core network level.

In terms of transmission equipment, a single transmitter/receiver is considered for cars, while two are considered for trains.

Typical applications/services are described in Section 4 with details of the corresponding traffic characterization. A mapping between these traffic types and those considered in other WPs of the project is also provided.

8 CONCLUSIONS

The Future Railway Mobile Communication System (FRMCS) will be the 5G worldwide standard for railway operational communications, conforming to European regulation as well as responding to the needs and obligations of rail organisations outside of Europe. The work on functional & technical requirements, specification & standardisation in 3GPP as well as regarding harmonised spectrum solutions is currently led by UIC, in cooperation with the whole railway sector. In this context, the 5GRAIL project aims at verifying the first set of FRMCS specifications and standards (FRMCS V1) by developing and testing prototypes of the FRMCS ecosystem. The validation of the latest available railway-relevant 5G specifications will be achieved through trials covering significant portions of railway operational communication requirements and including the core technological innovations for rail expected from 5G release 16 and pre-release 17.

In this context, the main objective of WP6 is the evaluation of the coexistence of rail and road automotive communication use cases. The possible synergies allowed by FRMCS between both vertical industries based on a situation implying common use cases will be evaluated. Thus, tthe objective of deliverable D6.1 is the identification and definition of possible rail and road coexistence scenarios. First, the coexistence scenarios from an infrastructure point of view are proposed in order to highlight the different situations. Three main cases are considered: tracks parallel to road, tracks crossing road (the level crossing and the tramways cases are differentiated) and the case of tunnels and bridges. After the description of the infrastructure point of view, the specific communication services in road and rail domains are detailed. Regarding the railway specific communication applications, the deliverable details in particular the FRMCS for train operation, the virtual coupling, the case of urban rail and the Train Control and monitoring system. Examples of Key Performance Indicators extracted from 3GPP documents are proposed. Then, the deliverable treated the coexistence question from a telecommunication point of view. Finally, a rigorous methodology for the definition and description of the coexistence scenarios was proposed. Using this methodology, five examples of typical coexistence scenarios are detailed.

Based on these coexistence scenarios, the next step, in WP6 Task 6.2, will be to identify the most relevant coexistence scenarios between road and rail domains. For these scenarios, as indicated in the GRANT, within Task 6.2 and Task 6.3, a proof of concept (PoC) demonstrator will be provided based on appropriate techniques for each of them (emulation, simulation, co-simulation or prototyping) and the considered KPIs, which will need to be defined (generic or case specific). A part of the tasks will be also to identify the suitable technologies and tools to provide such a PoC, within the limited scale of the task. Different parameters will be considered and impact on the defined KPIs evaluated. We will analyse the obtained results and we will draw conclusion of coexistence of Rail and Road communication.

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10 APPENDICES

10.1 List of use cases selected for 5GRAIL

In the following table, the use cases selected by the work package 1 to be tested within work package 3 and 4 in laboratory conditions and within work package 5 in-field conditions are mapped in the table describing traffic characteristics for main line rail scenarios (ref. 3GPP TS 22.289 V17.0.0 (2019-12).

Please note that the use cases of work package 6 have not been determined yet. This will be done in T6.2.

For a better understanding of the mapping of operational use cases, as presented in the following table, the definitions of the scenarios are added in the definitions table.

Table 12: Mapping of use cases to the traffic characteristics for main line rail scenarios.

Scenario	End-to-end latency	Reliability (Note 1)	Speed limit	User experienced data rate	Payload size (Note 2)	Area traffic density	Service area dimension (note 3)	Use cases (Ref.FU-7100, User Requirements Specification)
Voice Communication for operational purposes	≤100 ms	99,9%	≤500 km/h	100 kbps up to 300 kbps	Small	Up to 1 Mbps/line km	200 km along rail tracks	5.1 On-train outgoing voice communication from the train driver towards the controller(s) of the train 5.2 On-train incoming voice communication from the controller towards a train driver
Critical Video Communication for observation purposes	≤100 ms	99,9%	≤500 km/h	10 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks	5.27 Critical real time video
Very Critical Video Communication with direct impact on train safety	≤100 ms	99,9%	≤500 km/h	10 Mbps up to 20 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks	5.10 Automatic Train Operation communication (limited to GoA2 ATO)
	≤10 ms	99,9%	≤40 km/h	10 Mbps up to 30 Mbps	Medium	Up to 1 Gbps/km	2 km along rail tracks urban or station	5.13 Remote control of Engines
Standard Data Communication	≤500 ms	99,9%	≤500 km/h	1 Mbps up to 10 Mbps	Small to large	Up to 100 Mbps/km	100 km along rail tracks	6.9 On-Train Telemetry communications, 6.11 On-train remote equipment control , 6.20 Transfer of data
Critical Data Communication	≤500 ms	99,9999%	≤500 km/h	10 kbps up to 500 kbps	Small to medium	Up to 10 Mbps/km	100 km along rail tracks	5.9 Automatic Train Protection communication

Very Critical Data Communication	≤100 ms	99,9999%	≤500 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 10 Mbps/km	200 km along rail tracks	
	≤10 ms	99,9999%	≤40 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 100 Mbps/km	2 km along rail tracks	
Messaging	-	99.9%	≤500 km/h	100 kbps	Small	Up to 1 Mbps/km	2 km along rail tracks	N/A
NOTE 1: Reliability as defined in sub-clause 3.1. NOTE 2: Small: payload ≤ 256 octets, Medium: payload ≤512 octets; Large: payload 513 -1500 octets. NOTE 3: Estimates of maximum dimensions.								

Table 13: Use cases for operational railway purposes

URS Ref	Critical Communications Applications
5.1	On-train outgoing voice communication from the train driver towards the controller(s) of the train
5.2	On-train incoming voice communication from the controller towards a train driver
5.3	Multi-Train voice communication for drivers including ground user(s)
5.9	Automatic Train Protection communication
5.10	Automatic Train Operation communication (limited to GoA2 ATO)
5.13	Remote control of Engines
5.15	Railway Emergency Communication
5.27	Critical real time video (if not feasible due to stringent QoS, alternative is UC 6.13 - MCVideo is excluded)
5.28	Critical Advisory Messaging services- safety related
	Performance Communication Applications
6.9	On-Train Telemetry communications (TCMS includes 6.9 + 6.11 + 6.20)
6.11	On-train remote equipment control (TCMS includes 6.9 + 6.11 + 6.20)
6.13	Non-critical real time video (see clause 5.27) - MCVideo, MCData related
6.20	Transfer of data (TCMS includes 6.9 + 6.11 + 6.20)
6.22	Transfer of CCTV archives (Wi-Fi related)

10.2 Examples of key Performance Indicators for specific applications:

Here is an example of performance application, where KPIs are defined based on the requirements of 3GPP documents.

- Performance services specific KPIs reflecting the application requirements for the CCTV or other infrastructure monitoring services have been identified as follows (based also on 3GPP 22.889 V17.3.0, 3GPP 22.289 V17.0.0)
- "High-resolution Real-time Video Quality of CCTV camera stream towards the monitoring centre", reflects the CCTV service requirement for: data rates of ~3-15Mbps (average 6Mbps), available along the railway tracks.
- "Stream setup time", corresponds to the time between the moment that the CCTV service switching on is triggered on the device up to the moment that it is setup.
- "Total Traffic transferred from trains CCTV cameras to monitoring/ operations' centre", for the purposes of the use case two cameras facing front and back of the train will be installed, in normal operation, the number of cameras can be two per wagon/door/ etc.
- "Bulk transfer of infrastructure monitoring data (e.g., CCTV archives, engine performance measurement archives etc.), collected over time" it depends on the scheduling of the transfer, and the availability of the network, but it may amount a number of GB-TB, bulk transfer data rates of 500Mbps-1Gbps are advised 3GPP 22.889 V17.3.0, 3GPP 22.289 V17.0.0).

Table 14: Mapping between KPIs and requirements

Performance Services Requirements KPI mapping	SKPI	CKPI	Target
High-resolution Real-time Video Quality of CCTV camera stream towards the monitoring centre	High-resolution Real-time Video/Audio Quality	Packet Loss	<0.005
		Guaranteed Data Rate	3-15Mbps
		Jitter	<40ms
	Extensive network coverage	End-to-end Latency	150ms- not critical
		Packet Loss	<0.005
		Guaranteed Data Rate	3-15Mbps
		Availability	99.99%
		Connection Density	Not critical, 2/ wagon

Stream setup time	Service Setup Time	End-to-end Latency	Not critical: Latency <150ms Total stream setup time <1-2 sec.
		Availability	99.99%
Total Traffic transferred from trains CCTV cameras to monitoring/ operations' centre.	Area Traffic Density	Availability	99.99%
		Connection Density	Not critical, 2/ wagon, more depending on other monitoring devices
		Area Network Capacity	Low
Bulk transfer of infrastructure monitoring data (e.g. CCTV archives, engine performance measurement archives etc.), collected over time"	Area Traffic Density	Availability	99.99%
		Area Network Capacity	It depends on the scheduling of the transfer, and the availability of the network, but it may amount a number of GB-TB, so >500Mbps is desirable.

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