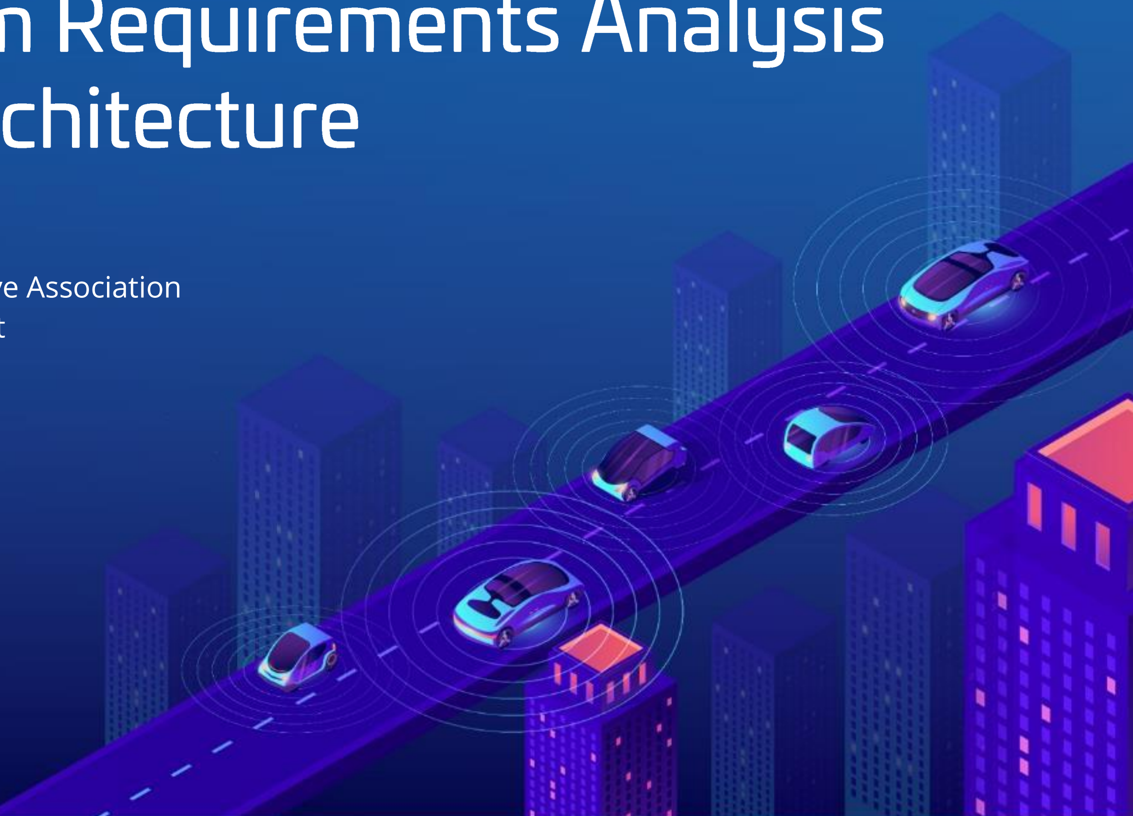
Tele-Operated Driving (ToD): System Requirements Analysis and Architecture

5GAA Automotive Association
Technical Report



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VERSION:	Version 1.02
DATE OF PUBLICATION:	15 September 2021
DOCUMENT TYPE:	Technical Report
EXTERNAL PUBLICATION:	Yes
DATE OF APPROVAL BY 5GAA BOARD:	26 July 2021

Contents

Foreword

This Technical Report has been produced by 5GAA.

The contents of the present document are subject to continuing work within the Working Groups (WG) and may change following formal WG approval. Should the WG modify the contents of the present document, it will be re-released by the WG with an identifying change of the consistent numbering that all WG meeting documents and files should follow (according to 5GAA Rules of Procedure):

x-nnzzzz

(1) This numbering system has six logical elements:

(a) x: a single letter corresponding to the working group:

where x =

T (Use cases and Technical Requirements)

A (System Architecture and Solution Development)

P (Evaluation, Testbed and Pilots)

S (Standards and Spectrum)

B (Business Models and Go-To-Market Strategies)

(b) nn: two digits to indicate the year. i.e. ,17,18 19, etc

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(2) No provision is made for the use of revision numbers. Documents which are a revision of a previous version should indicate the document number of that previous version

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Introduction

Tele-Operated Driving (ToD) technology assists, complements, and accelerates semi- and fully automated driving in various scenarios. This 5GAA technical report studies system requirements and corresponding enabler technologies for ToD services using Cellular-V2X (C-V2X) networks. The study covers the vehicle sub-system, ToD operator sub-system, infrastructure sub-system, and C-V2X networks for end-to-end deployment of ToD services. System application layer architectures and the underlying communication network architectures for different ToD use cases and scenarios are presented in this study with the focus on interfaces among different stakeholders and with considerations on service interoperability in multi-OEM, multi-Service Provider, multi-RTA and multi-MNO environments. This study also envisages that market deployment of ToD services will follow a multi-stage roadmap, starting from confined areas, then evolving into dedicated public roads and areas, and finally covering cross-region (long-haul) mobility of automated vehicles.

This technical report is organised as follows: Section 4 summarises ToD use cases and scenarios from 5GAA ToD Task 1 [2] and presents a visionary roadmap of ToD services. Section 5 presents the system-application layer architecture of ToD services in different stages of the roadmap. Functional and performance requirements of each ToD sub-system are analysed in Section 6, followed by introductions of technologies addressing such requirements in Section 7. Section 8 focuses on the communication architectures supporting ToD services based on 4G and 5G cellular networks. Section 9 concludes the report.

1 Scope

The present document is the second deliverable of 5GAA XWI Tele-Operated Driving (ToD). This deliverable addresses Task 2 of the ToD XWI [1] by analysing functional and non-functional requirements of ToD systems for the prioritised use cases and scenarios from deliverable D1.1 [2]. Analysis in the present document covers not only connectivity, but also vehicle, ToD operator, and infrastructure sub-systems for end-to-end ToD systems. This deliverable also studies communication network features and architecture fulfilling the requirements of ToD services.

2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies.

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3 Definitions, symbols, and abbreviations

3.1 Definitions

Void

3.2 Symbols

Void

3.3 Abbreviations

For the purposes of the present document, the following symbols apply:

5GC 5G Core Network

5GS	5G System
5QI	5G QoS Identifier
ADAS	Advanced Driver Assistance Systems
AF	Application Function
AGV	Automated Guided Vehicle
AMF	Access and Mobility Management Function
AMQP	Advanced Message Queueing Protocol
APP	Application
ARP	Allocation and Retention Priority
AS	Application Server
ASIL	Automotive Safety Integrity Level
AV	Automated Vehicle
AVF	Architectural Vulnerability Factor
AVP	Automated Valet Parking
AVPS	Automated Valet Parking System
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
CN	Core Network
CNN	Convolutional Neural Networks
CPM	Collective Perception Message
DATEX II	Data Exchange II
DDT	Dynamic Driving Task
DENM	Decentralised Environmental Notification Message
FPGA	Field-programmable Gate Array
G2G	Glass-to-Glass
GBR	Guaranteed Bit Rate
GFBR	Guaranteed Flow Bit Rate
GPS	Global Positioning System
GPU	Graphics Processing Unit
HPLMN	Home PLMN
HRC	Human Remote Control
HSS	Home Subscriber Server
HV	Host Vehicle

IPX	IP Exchange
ISO	International Organisation for Standardisation
ITS	Intelligent Transport Systems
IVIM	In-Vehicle Information Message
LoA	Level of Automation
MFBR	Maximum Flow Bit Rate
MNO	Mobile Network Operator
MAC	Multiply and Accumulate
MAPEM	Map (topology) Extended Message
MME	Mobility Management Entity
MNO	Mobile Network Operator
MOS	Mean Opinion Score
MRC	Machine Remote Control
NEF	Network Exposure Function
NF	Network Function
NG-RAN	Next Generation Radio Access Network
NLOS	Non Line of Sight
NRF	Network Repository Function
NRI	Network Reselection Improvement
NWDAF	Network Data Analytics Function
OEM	Original Equipment Manufacturer
ODD	Operational Design Domain
OOD	Out of Distribution
PCF	Policy Control Function
PDB	Packet Delay Budget
PF	Prediction Function
PGW	Packet data Gate Way
PLMN	Public Land Mobile Network
PSNR	Peak Signal-to-Noise Ratio
PVF	Program Vulnerability Factor
QFI	QoS Flow ID
QoS	Quality of Service
RAN	Radio Access Network

RLC	Radio Link Control
RQA	Reflective QoS Attribute
RSS	Responsibility Sensitive Safety
RSU	Road Side Unit
RTA	Road Traffic Authority
RTK	Real Time Kinematic
SCEF	Service Capability Exposure Function
SDSM	Sensor Data Sharing Message
SGW	Serving Gateway
SIM	Subscriber Identification Module
SLR	Service Level Requirement
SOTIF	Safety Of The Intended Functionality
SMF	Session Management Function
SP	Service Provider
SPATEM	Signal Phase and Timing Extended Message
SREM	Signal Request Extended Message
SSEM	Signal request Status Extended Message
STiCAD	Safety Treatment in Connected and Automated Driving
ToD	Tele-Operated Driving
TVF	Timing Vulnerability Factor
UDF	Unified Data Repository
UDM	Unified Data Management
UE	User Equipment
UPF	User Plane Function
V2X	Vehicle-to-Everything
VPLMN	Visited PLMN
VMS	Variable Message Signs
VPN	Virtual Private Network
VPU	Vision Processing Unit
VQEG	Video Quality Expert Group
WG	Working Group

4 ToD use cases and scenarios

4.1 Summary of ToD use cases and scenarios from 5GAA ToD task 1 [1]

The deliverable produced by Task 1 within this 5GAA Tele-Operated Driving (ToD) cross-work item [1] reported the analysis, extension and classification of a set of ToD use cases. This was done with the aim of providing a shortlist, which would serve as a basis for further activities related to technical requirement derivation and business considerations. A survey on the state of the art was performed, analysing existing (pre-)commercial solutions and highlighting major outcomes and guidelines, as useful input to shape and guide ToD developments. A review of the main achievements of previous and ongoing R&D projects in the automotive domain was also made with the same purpose. The survey ended with the lessons learned and recommendations.

After this, each use case, with its corresponding scenarios, was further analysed. ToD use cases from 5GAA Working Group 1 (WG1) were taken as initial input and extended in the scope of multi-OEM, multi-MNO, and multi-Road Traffic Authority (RTA) scenarios. Additional service operation scenarios were also considered, taking realistic and operational situations into account. For each use case, the deliverable provided its rationale, an overall description, and the related information flows. The outcome of this work was a subset of use cases and scenarios whose requirements could influence architecture design and technical studies in further ToD tasks. Table 1 presents the resulting shortlist of scenarios grouped by factors which can most influence their architecture and deployment.

Table 1: Summary of use cases from Task 1

Characteristics	Use Case / Scenario
Indirect Control ToD[1] Single-OEM Single-MNO Single-ToD provider Confined area of operation	• *Tele-Operated Driving* (Section 5.4.10 of [33]) with 'Remote Driving Paths' in factories, ports, parking lots and other confined areas. • *Tele-Operated Driving Support* (Section 5.4.11 of [33]) with 'Remote Driving Paths', sending manoeuvre instructions and trajectory to vehicle fleet in a green zone. • *Tele-Operated Driving for Automated Parking* (Section 5.4.12 of [33]) with 'Remote Driving Paths' in automotive OEM factories.
Indirect Control ToD Multi-OEM Multi-MNO Single-ToD provider Confined area of operation	• *Tele-Operated Driving for Automated Parking* (Section 5.4.12 of [33]) with 'Remote Driving Paths' for a fleet of vehicles using communication services from different mobile network operators in garages or seaports.
Direct Control ToD Single-OEM Single-ToD provider Unconfined area of operation (open roads)	• *Tele-Operated Driving* (Section 5.4.10 of [33]) with 'Remote Driving service'. • from a certain port to the destination city from an area outside the city , for example the airport, to the city centre (car-sharing)
Direct Control ToD Single-OEM	• *Tele-Operated Driving Support* (Section 5.4.11 of [33]) with 'Remote Steering', providing remote driving service to vehicle fleet in a green zone.

[1] The Types of ToD are defined in 5GAA ToD XWI Deliverable 1.1 [2].

Single-ToD provider Confined area of operation or following pre-determined route	• *Tele-Operated Driving Support* (Section 5.4.11 of [33]) with 'Remote Steering' in automotive OEM factories, allowing only authorised staff to enter, e.g. trained workers.
Direct Control ToD Multi-OEM Single-ToD provider Confined area of operation or following pre-determined route	• *Tele-Operated Driving Support* (Section 5.4.11 of [33]) with 'Remote Steering' for a fleet of vehicles from a legacy fleet provider in garages or seaports. • *Tele-Operated Driving Support* (Section 5.4.11 of [33]) with 'Remote Steering' for a fleet of Automated Guided Vehicles (AGVs).

Infrastructure required
 	
ToD operator is human
 	
Multi-OEM
 	
Single MNO
 	
Multi-RTA
 	
Confined area of operation or following pre-determined route
	• *Infrastructure-based Tele-Operated Driving* (Section 5.4.8 of [33]) (ToD operator is human)
	  • in special zones like harbours, airports, or factory grounds
	  • provided by ToD operator associated with the road section or zone

Infrastructure required
 	
ToD operator is machine
 	
Multi-OEM
 	
Single MNO
 	
Multi-RTA
 	
Confined area of operation or following pre-determined route
	• *Infrastructure-based Tele-Operated Driving* (Section 5.4.8 of [33]) (ToD operator is machine)
	  • in special zones like harbours, airports, or factory grounds
	  • provided by ToD operator associated with the road section or zone

Additional to the use case classification, a set of functional requirements was derived, focusing on aspects such as communication, network, vehicle, ToD operator and availability of information. These are summarised in Table 2.

Table 2: Summary of ToD functional requirements from Task 1

ToD Component	Functional Requirements
Communication and Network	• The ToD operator should establish a mutually authenticated and secure communication session with the vehicle. • Service continuity should be guaranteed during the operation of ToD service. • The communication link should be reliable and encrypted. • Real-time response and high reliability of the communication session should be maintained, when the vehicle drives through national borders, or needs to roam between different MNOs or operate under different RTAs of different geographical regions. • The network should be able to send notifications about expected QoS change (i.e. QoS prediction)

	to vehicles and the ToD operator, if such notifications are available.
Information	• The ToD operator should receive reliable information about the vehicle's capabilities before the ToD Service takes place. • Trustworthy and reliable information about the environment, e.g. HD map of the parking area, green zones, should be made available to the ToD operator. • The ToD operator should be informed about any authorised or unauthorised access to the confined area, e.g. by applying admission control. • Note: The ToD operator may also receive sensor information from the vehicle.
Vehicle	• The vehicle should be able to know its own geographical position and send it to the ToD Service Provider when required. For Indirect Control ToD [2] • The vehicle should be capable of following remote trajectories, e.g. being capable of and engaging automated driving of level 4 [19] or higher. For ToD Direct Control [2] • The vehicle should be capable of processing remote actuator commands • The vehicle should receive from the ToD operator manoeuvre instructions and executes them, according to the vehicle's on-board security checks • The vehicle should be able to receive notifications about expected QoS change (i.e. QoS prediction), if such notifications are available, and then appropriate adaptations should be applied (e.g. reduce speed, enable safe operation etc.)
ToD operator	• The ToD operator should be able to receive notifications about expected QoS change (i.e. QoS prediction), if such notifications are available, and then appropriate adaptations should be applied.
	• Liability among vehicle, ToD operator, and facility (e.g. parking facility), should be clarified based on related certification and authorisation of each party.

Others	• Service subscription and payment may be required either through vehicle OEM or vehicle owner. • Authentication should be required for subscribed service. • Authentication and charging solutions may be required for ToD service provisioning. • Privacy protection should be applied, if applicable according to local regulations. • The interface between ToD operator and vehicles from different OEMs should be standardised, if cross-OEM and cross ToD Service Provider interoperability is required.

4.2 ToD services roadmap

Based on the work in ToD Task 1 [2], this study envisages a progressive multi-stage deployment roadmap for ToD services in different operational environments. As shown in Figure 1, the envisaged ToD service roadmap consists of three stages, namely ToD in confined areas, ToD in dedicated local public roads or areas, and ToD for cross-region mobility. Representative ToD use cases and scenarios are mapped to corresponding stages in the roadmap with highlights on the type of ToD services[2]. It is foreseen that the market rollout of ToD services follows this three-stage roadmap to assist, complement and accelerate the realisation of connected and automated mobility, e.g. as shown in the 5GAA roadmap for advanced driving use cases [24].

In each stage, the type of ToD services can be either Indirect Control or Direct Control depending on the use case. In Direct Control ToD, driving automation of SAE L2 or lower may be engaged on the vehicle during the ToD operation, while the ToD operator performs the rest of real-time Dynamic Driving Tasks (DDT) [19]. In case no driving automation is engaged on the vehicle during the ToD operation, i.e. SAE L0, the ToD operator performs all real-time DDT, e.g. in automated factory parking in Stage 1 or Automated Valet Parking Type 2 [23] in Stage 2. For Indirect Control ToD and Dispatch ToD services, SAE driving automation Level 4 or higher may need to be engaged on the vehicle during the ToD operation, to allow the vehicle to perform all real-time DDT following the route and/or pathway information provided by the ToD operator.

[2] The Types of ToD are defined in 5GAA ToD XWI Deliverable 1.1 [2].

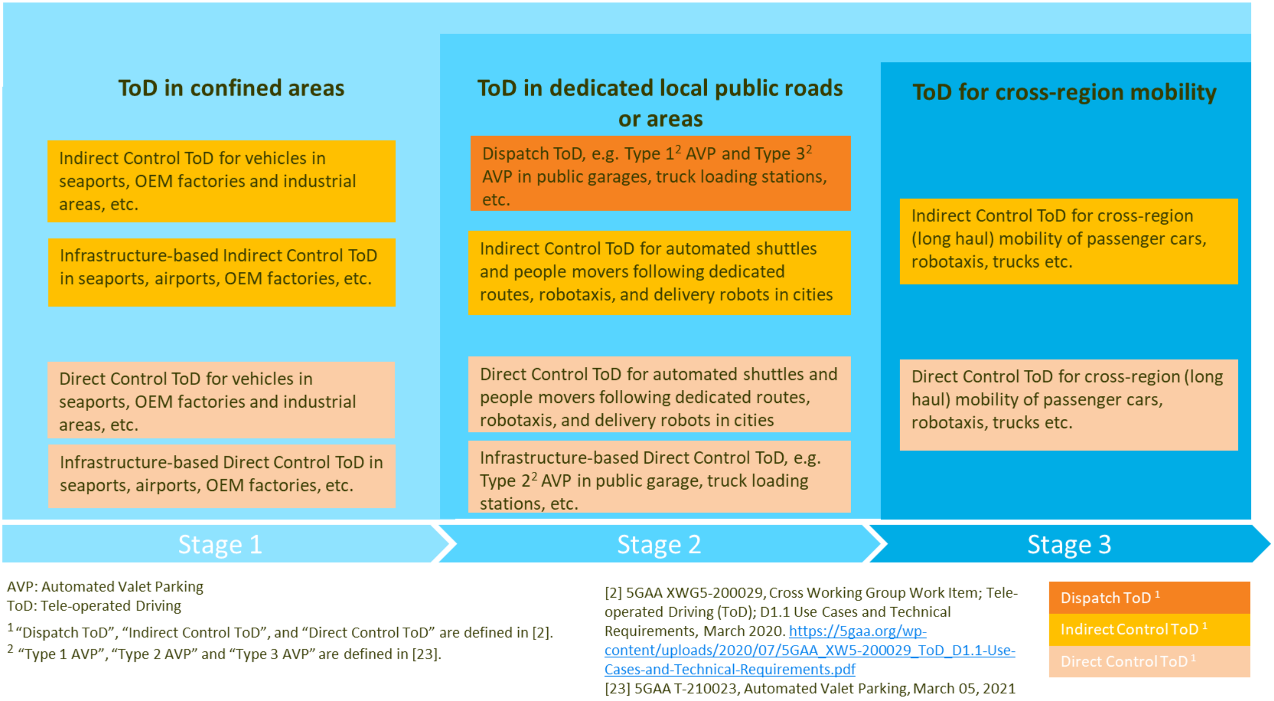

Figure 1: A visionary roadmap for ToD services

- Stage 1: ToD in confined areas

In this stage, ToD services are provided to vehicles operating in confined areas, e.g. seaports, OEM factories, industrial areas, etc. Such areas usually have restricted access control for human and other traffic. The operational environments, including necessary infrastructure supports, in this stage are under the full control of the premise owner, which in many cases is also the ToD Service Provider.

In this stage, ToD services are usually provided to the vehicle fleet from a single automotive OEM. ToD systems may include infrastructure support from the premises owner or the ToD Service Provider. Usually, a dedicated communication network or public communication network from a single MNO is used for supporting the ToD use case in confined areas.

ToD use cases specified by 5GAA that are related to this stage include Tele-operated Driving (Section 5.4.10 of [33]), Tele-Operated Driving Support (Section 5.4.11 of [33]), Tele-Operated Driving for Automated Parking (Section 5.4.12 of [33]), and Infrastructure-based Tele-Operated Driving (Section 5.4.8 of [33]). The remote control of AGVs in confined industrial areas is also a ToD scenario in this stage.

- ToD in dedicated local public roads or areas

In this stage, ToD services are provided to vehicles operating in dedicated local public roads or areas, e.g. in a city. Typical ToD scenarios in this stage include:

- Support to automated shuttles, buses, and other vehicles primarily for transport of people and for last-mile mobility services that operate following predetermined routes on public roads in a city.
- Infrastructure-based Automated Valet Parking services for automated passenger vehicles in public garages or for logistics trucks in automated truck loading stations.
- Robotaxis and delivery robots operating in a city.

As the vehicles are operated on public roads or in public garages in this stage, the ToD system and operator need to be able to handle interactions with other road users, including other vehicles and vulnerable road users, in a safe manner.

In this stage, ToD services can be provided to a vehicle fleet from a single automotive OEM or vehicles from different automotive OEMs. Infrastructure supports from the ToD Service Providers or road operators may be available, e.g. for the use case Automated Valet Parking (AVP) for Automated Vehicles (AVs) in a public garage [23]. The communication network covering the service area, which is a city or dedicated parking garage, can be built by a single or multiple MNOs.

Dispatch ToD, as defined in [2], is also a valid operation mode. For example, in AVP for highly automated vehicles (L4+) in public garages, the parking Service Provider can only provide the digital map and the route information to the destination parking lot, as described in [23].

ToD use cases specified by 5GAA that are related to this stage include Tele-Operated Driving (Section 5.4.10 of [33]), Tele-Operated Driving Support (Section 5.4.11 of [33]), Tele-Operated Driving for Automated Parking *(Section* 5.4.1*2 of [33])*, Infrastructure-based Tele-Operated Driving *(Section* 5.4.*8 of [33])*, and T-210023.

- ToD for cross-region mobility

In this stage, ToD services are provided for cross-region (long haul) mobility using public roads. Dedicated lanes for automated vehicles on highway, country roads, or in urban areas, may be available. Vehicles using ToD services may share the public roads with other automated vehicles, separated from normal (non-automated) vehicles and road users. Multiple ToD Service Providers may provide ToD services on the same cross-region corridor. In the future, once legal and safety challenges are resolved, automated vehicles may also share the same lane with non-automated vehicles.

In this stage, ToD services can be provided to the vehicle fleet from a single automotive OEM or vehicles from different automotive OEMs, e.g. passenger cars. Infrastructure supports from road operators can be expected but not guaranteed due to the broad area that the service is provided. Communication networks from multiple MNOs are used, if the network from a single MNO cannot provide full coverage for the service area, e.g. when the corridor is across a country border.

ToD use cases specified by 5GAA that are related to this stage include Tele-Operated Driving (Section 5.4.10 of [33]), Tele-Operated Driving Support (Section 5.4.11 of [33]), and Infrastructure-based Tele-Operated Driving (Section 5.4.8 of [33]).

Table 1 summarises characteristics of ToD scenarios in different stages of the roadmap.

Table 3: Characteristics of ToD scenarios in three stages of the roadmap

Stages	Service scenarios	ToD Service Provider	OEM	RTA	MNO
Stage 1: ToD service in confined areas	For vehicles in seaports, OEM factories, and industrial areas, etc. (Indirect Control ToD or Direct Control ToD)	Single	Single	(Note applicable)	Single
	Infrastructure-based ToD in seaports, airports, OEM factories, etc. (Indirect Control ToD or Direct Control ToD)	Single	Single	(Note applicable)	Single
Stage 2: ToD service in dedicated local public roads or areas	Automated shuttles or people movers with predetermined route (Indirect Control ToD or Direct Control ToD)	Single	Single	Single (pre-determined route in city)	Single / Multiple
	(Infrastructure based) Automated Valet Parking in public garages (Dispatch ToD, Indirect Control ToD or Direct Control ToD)	Single / Multiple	Multiple	(Note applicable)	Single / Multiple

	Regional robotaxis or delivery robots (Indirect Control ToD or Direct Control ToD)	Single / Multiple	Single / Multiple	Single	Single / Multiple
Stage 3: ToD service for cross-region mobility on public roads	ToD for cross-region (long haul) mobility of passenger cars, robotaxis, trucks, etc. (Indirect Control ToD or Direct Control ToD)	Multiple	Multiple	Multiple	Multiple

5 System application layer architecture of ToD

5.1 5GAA V2X application layer reference architecture

The functional view of the agreed 5GAA V2X Application Layer Reference Architecture [3] is described in Figure 2.[3]

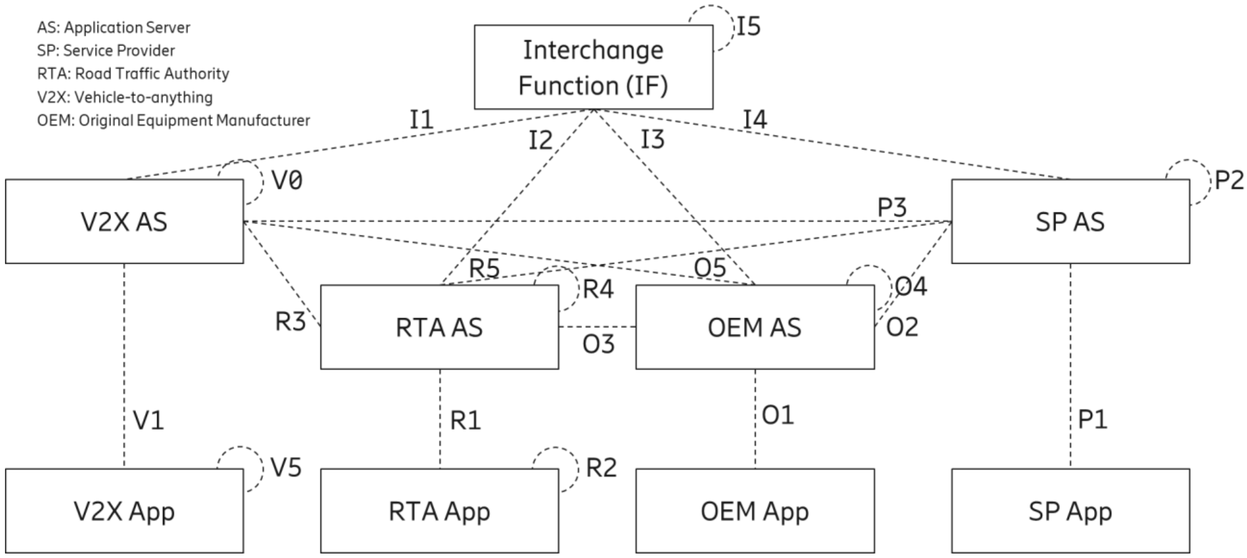

Figure 2: 5GAA V2X application layer reference architecture

Every reference point in Figure 2 represents an application layer connection between the two functional components. The description of functional components and reference points can be found in section 6.4 and section 6.5 of [3], respectively.

Each V2X use case has its application layer architecture based on the reference architecture in Figure 2. From the deployment perspective, such architecture also varies for different scenarios. The next section describes the application layer architecture of ToD in scenarios summarised in Chapter 4 of the present report.

5.2 Deployment views of system application layer architecture for ToD services

The deployment views of ToD application layer architecture illustrate the functional components and reference points from the reference architecture in Figure 2 that are required for the deployment of ToD services in different scenarios. This views also illustrate the role of stakeholders in the deployment.

5.2.1 General deployment view of ToD application layer architecture

Figure 3 illustrates the general deployment view of ToD application layer architecture. Subsection 5.2.1.1 and 5.2.1.2 describe functional components and interfaces, respectively. Section 5.2.2 provides example deployment architectures in selected scenarios.

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[3] Application (App) and Application Server (AS) are defined in [3] section 6.3.1 generic function view of V2X application layer reference architecture.

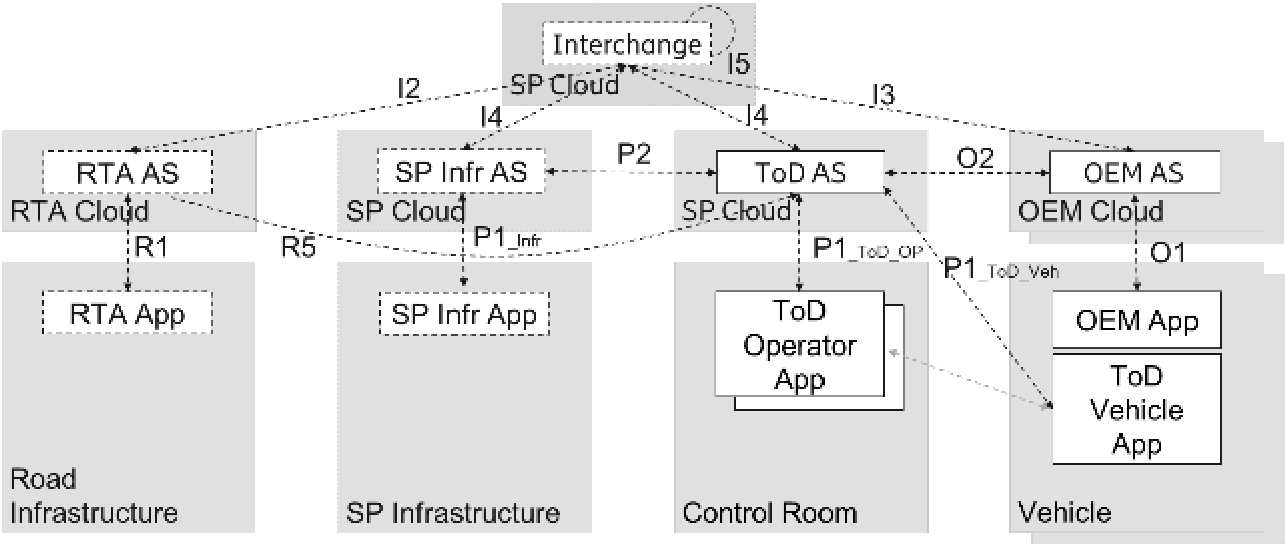

Figure 3: General deployment view of application layer architecture for ToD services

ToD Application Server (ToD AS), ToD Operator Application (ToD Operator App), OEM Application Server (OEM AS), OEM Application (OEM App), and ToD Vehicle Application (ToD Vehicle App) are essential components for all ToD use cases and scenarios. ToD in some scenarios may also require information and data from the infrastructure[4], e.g. information from traffic lights and Variable Message Signs (VMS) or data from sensors on or in the infrastructure. Therefore, Figure 3 also includes optional functional components Road Traffic Authority Application Server (RTA AS), Road Traffic Authority Application (RTA App), Service Provider Infrastructure Application Server (SP Infr AS), and Service Provider Infrastructure Application (SP Infr App), providing information and data from road and Service Provider infrastructures. The Interchange function in Figure 3 is for improving the scalability of the system when the number of application servers needing to be interconnected is large. It is also an optional functional component. As an alternative to using the Interchange function, application servers in the backend may also be connected directly with one another using secure links, if scalability of the system is not a concern.

As low end-to-end latency is critical for ToD, if it is possible the most efficient implementation could be integrating several functional components in a single App block to support the fastest path for some of the messages. For example, when an automotive OEM also takes the role of ToD Service Provider, the messages flow OEM ToD Vehicle App <-> OEM AS <-> ToD AS <-> ToD Operator App could be implemented, depending on the ToD scenarios in the most compacted blocks (i.e. linking OEM AS libraries in the ToD AS or vice versa).

Some secure implementations could support encrypted messages between the ToD Operator App and the OEM ToD Vehicle App that do not involve any other application in the communication flow. In this case, after the establishment of a secured link, e.g. via VPN, with the required certificates and Apps authorisations exchanged on request or in a pre-phase, the messages will be encrypted.

5.2.1.1 Application layer architecture components and stakeholders' roles

5.2.1.1.1 Tele-Operated Driving Application Server (ToD AS)

The ToD AS enables secure communication between the trusted ToD Operator App and ToD Vehicle App controlled by the OEM AS in the cloud and OEM APP on the vehicle. It manages registration and authentication requests from ToD Operator Apps and from ToD Vehicle Apps. The ToD AS supports the ToD Operator App and ToD Vehicle App from one or more ToD technology providers and offers a discovery service[5] if needed. It handles ToD service requests from either a ToD Operator App or a ToD Vehicle App.

Note: Access to the ToD Vehicle App should be controlled by the OEM AS in the cloud and the OEM App on the vehicle. In some scenarios, when latency becomes critical for ToD services, the OEM AS and OEM App may allow

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[4] As analysed in [2], scenarios B.2 of use case Tele-Operated Driving *(Section* 5.4.10 *of [33])* and A.2 and B.2 of use case Infrastructure-based Tele-Operated Driving *(Section* 5.4.*8 of [33])* require information from infrastructure.

[5] Because ToD solutions from different ToD technology providers may not be compatible with one another, the ToD AS may provide the discovery service for ToD Vehicle Apps to find the compatible ToD Operator App.

direct communication between the ToD AS and ToD Vehicle App, but a secure and trusted connection between the ToD AS and ToD Vehicle App should be established under the control of the OEM AS and OEM App.

The ToD AS may also provide functionalities for vehicle operation in normal situations, e.g. vehicle status monitoring, geofencing, and dispatching, before the vehicle needs Indirect Control ToD or Direct Control ToD services. In this case, the ToD AS may detect an abnormal situation affecting vehicles and trigger the ToD service.

The ToD AS may have interfaces with the RTA AS and/or SP Infr AS for securing information and data from road infrastructure and/or SP infrastructure, e.g. traffic light information and camera sensor data from the infrastructure.

The ToD AS may have interfaces with underlying communication networks to utilise network features, e.g. QoS support.

The ToD AS is deployed by the ToD Service Provider in the SP cloud.

5.2.1.1.2 Tele-Operated Driving Operator Application (ToD Operator App)

The ToD Operator App provides ToD Operator functionalities in ToD services. Functionalities include receiving information and data from ToD Vehicle App, RTA AS, and/or SP Inf AS, supporting the ToD operator in building environmental perception, performing the driving tasks, transmitting commands to ToD Vehicle App, etc.

The ToD Operator App includes all resources and hardware and software components covered by a ToD operator, including human-machine interfaces (HMI displays and speakers) for ToD operator perception, steering wheel, gear stick and pedals for longitudinal and lateral control of the vehicle, communication unit, and ToD operator (human or machinery).

The ToD Operator App establishes a secure communication session with trusted ToD Vehicle Apps via ToD AS and under the control of the corresponding OEM AS.

The ToD Operator App is deployed by a ToD Service Provider in the control room using technologies from ToD technology providers.

5.2.1.1.3 Original Equipment Manufacturer Application Server (OEM AS)

The OEM AS is the trust anchor for all vehicles from this automotive OEM. The OEM AS communicates with the OEM App and is responsible for secure and trusted remote access from or to vehicles.

The OEM AS may provide OEM Apps the information about trusted ToD AS and ToD Operator Apps.

The OEM AS is owned and deployed by a car OEM in an OEM cloud.

5.2.1.1.4 Original Equipment Manufacturer Application (OEM App)

The OEM App integrates services offered by the OEM AS to vehicles. For ToD services, the OEM App communicates with OEM AS and is responsible for secure and trusted remote access from or to vehicles.

The OEM App communicates with the ToD Vehicle App using internal interfaces in a vehicle and manages inbound and outbound connections for the ToD Vehicle App. The OEM App also manages the access of ToD Vehicle App to the vehicle interface (vehicle bus).

The OEM App is owned and deployed by a car OEM in vehicles.

5.2.1.1.5 Tele-Operated Driving Vehicle Application (ToD Vehicle App)

The ToD Vehicle App provides all functionalities and software/hardware components on a vehicle for ToD operation with a ToD Operator App. Functionalities include detecting an abnormal event and requesting ToD support, collecting and sending senor and camera data to the ToD Operator App, receiving and executing commands from ToD Operator App, etc.

The ToD Vehicle App includes software and/or hardware components offered by a ToD technology provider and utilises the vehicle interfaces from the automotive OEM for vehicle integration.

For security reasons, external ToD Vehicle App communications and access of the ToD Vehicle App to the vehicle interface are managed by the OEM AS via OEM App.

The OEM ToD Vehicle App is deployed by an OEM in vehicles using technologies provided by a ToD technology provider.

5.2.1.1.6 Road Traffic Authority Application Server (RTA AS)

The RTA AS offers traffic efficiency and traffic safety information to ToD Operator Apps via the ToD AS. Furthermore, RTA AS manages road infrastructure, such as variable road signs, traffic lights and video surveillance cameras.

The RTA AS is deployed by the RTA in the RTA cloud.

5.2.1.1.7 Road Traffic Authority Application (RTA App)

The RTA App integrates the services offered by the RTA AS into the road infrastructure.

The RTA AS is deployed by the RTA on the road infrastructure.

5.2.1.1.8 Service Provider Infrastructure Application Server (SP Infr AS)

The SP Infr AS offers infrastructure management and monitoring capabilities to the Service Provider Infrastructure Application for the deployment of the ToD Application.

This AS could support the physical or cloud deployment of the components in some geographic localisations, responsible for increasing or decreasing the required resources to meet a given QoS service that guarantees minimal performance for the supported use cases.

The monitoring supervision capabilities will be another relevant role of the SP Infr AS, gathering all the required data for the different metrics needed by ToD end users. Relevant KPIs for this ToD could be generated or integrated in the application servers to support the required quality.

These AS could be the orchestrator of all or some of the involved Application Servers. In the event more than one Service Provider is involved, the handover of the provider will be implemented by this AS.

5.2.1.1.9 Service Provider Infrastructure Application (SP Infr App)

The Infr AS is supported by the Service Provider Infrastructure Application Server and will be used for operators to monitor and control the deployment of ToD applications.

Service Provider Operators will be able to generate quality metrics for the OEM manufacturers, for the ToD operators, for the Infrastructure Operators, for the Service Provider or for the Road Infrastructure Operators.

The application could be used to increase or decrease the capacity of the ToD deployment, or to define geo-localisation rules enabling or disabling some supported use cases for certain road infrastructures or to some users.

5.2.1.1.10 Interchange Function (Interchange)

Given the large number of different RTA and SP Infrastructure in the world, Interchange Functions are needed to scale up and secure the message exchanges between RTA ASs, OEM ASs and SP ASs. The Interchange Function can be deployed by a SP, a Mobile Network Operator, or an RTA. In multi-SP and multi-OEM scenarios, an example implementation of Interchange Function can be a digital map provider who allows ToD SPs to announce or publish ToD service offers through its map platform (i.e. so automotive OEMs using the map platform can discover such services).

5.2.1.2 Interfaces

This subsection provides an overview of the application layer interfaces identified in the general deployment view of the ToD system in Figure 3. The exact protocols and message formats used by each interface depend on the use case and scenario, which are discussed in subsection 5.2.3 for different ToD stages.

5.2.1.2.1 Tele-Operated Driving (ToD) Service Provider interfaces

$P1_{\_ToD\_OP}$: the interface connects the ToD AS and ToD Operator App. This secured interface is for the ToD AS to configure the ToD Operator App during a ToD service session. This interface also conveys user plane data between the ToD Operator App and ToD Vehicle App, and between the ToD Operator App and SP Infr App during a ToD session.

A ToD AS may connect to multiple ToD Operator Apps from different ToD technology providers. This interface may use standard or proprietary protocols from ToD technology providers.

$P1_{\_ToD\_Veh}$: the interface connects the ToD AS and ToD Vehicle App. This is used for secure connection between trusted ToD AS and ToD Vehicle Apps under the control of the OEM AS and OEM App for conveying user plane data between the ToD Operator App and ToD Vehicle App via the ToD AS. This interface may use standard or proprietary protocols from ToD technology providers. In ToD scenarios requiring cross-OEM and ToD Service Provider interoperability, this interface needs to be standardised. This interface is usually implemented using cellular mobile communications.

P2: the interface connects the ToD AS and SP Infr AS in order for the ToD AS to configure the SP Infr AS, initiating and terminating infrastructure support to a ToD session. This interface also conveys user plane data between the SP Infr App and ToD Operator App via the SP Infr AS and ToD AS during a ToD session. This interface may use proprietary protocols and is typically implemented via secured connections between trusted actors in the backend.

5.2.1.2.2 Original Equipment Manufacturer (OEM) interfaces

O1: the interface connects the OEM AS and OEM App via secured communication between the OEM backend and trusted vehicles. This secured interface is for the OEM AS to configure the vehicle, initiating and terminating the ToD service sessions, and to convey user plane data between the ToD Vehicle App and ToD operator App during a ToD session. Depending on the ToD use case and scenario, this interface may use standard or proprietary protocols for ToD services.

O2: the interface connects the OEM AS and ToD AS for initiating and terminating ToD service sessions, as well as conveying user plane data between the ToD Vehicle App and ToD operator App during a ToD session. This interface may use a proprietary protocol, or a standard protocol if multi-OEM support is required. This interface is typically implemented via secured connections between trusted actors in the backend.

5.2.1.2.3 Road Traffic Authority (RTA) interfaces

R1: the interface connects the RTA AS and RAT App. This interface uses standard protocols and is under the control of the road operator.

R5: the interface connects the RAT AS to ToD AS. This interface uses standard protocols and is typically implemented via secured connections between trusted actors in the backend.

5.2.1.2.4 Service Provider Infrastructure (SP Infr) interfaces

$P1_{\_Infr}$: the interface connects the SP Infr AS and SP Infr App in order for the SP Infr AS to configure the SP Infr App (e.g. infrastructure sensors) and to convey user plane data between the SP Infr AS and SP Infr App during a ToD session. This interface may use proprietary protocols.

5.2.1.2.5 Interchange Function (Interchange) interfaces

I2: the interface connects Interchange and RTA AS.

I3: the interface connects Interchange and OEM AS.

I4: the interface connects Interchange and Service Provider AS, such as the ToD AS and SP Infr AS.

I5: the interface connects different Interchange Functions.

Interchange Function interfaces are typically implemented via secured connections between trusted actors in the backend.

5.2.2 Example deployment architectures in different ToD scenarios

5.2.2.1 ToD services in confined areas (example in ToD Stage 1)

Figure 4 shows the deployment view of ToD architecture in confined areas, e.g. a typical service of ToD Stage 1 is automated car parking in automotive OEM factories.. All system components in this scenario are under the control of the premises owner, i.e. the automotive OEM. There is no requirement on interoperability across OEMs and Service Providers. Therefore, proprietary protocols can be used on all interfaces. Communication between vehicles and the OEM cloud can be realised using dedicated cellular networks or public mobile networks from an MNO, e.g. via network slicing. Table 4 summaries the interfaces in this architecture for ToD in confined areas.

Note: This architecture is applicable to both Indirect Control ToD and Direct Control ToD services.

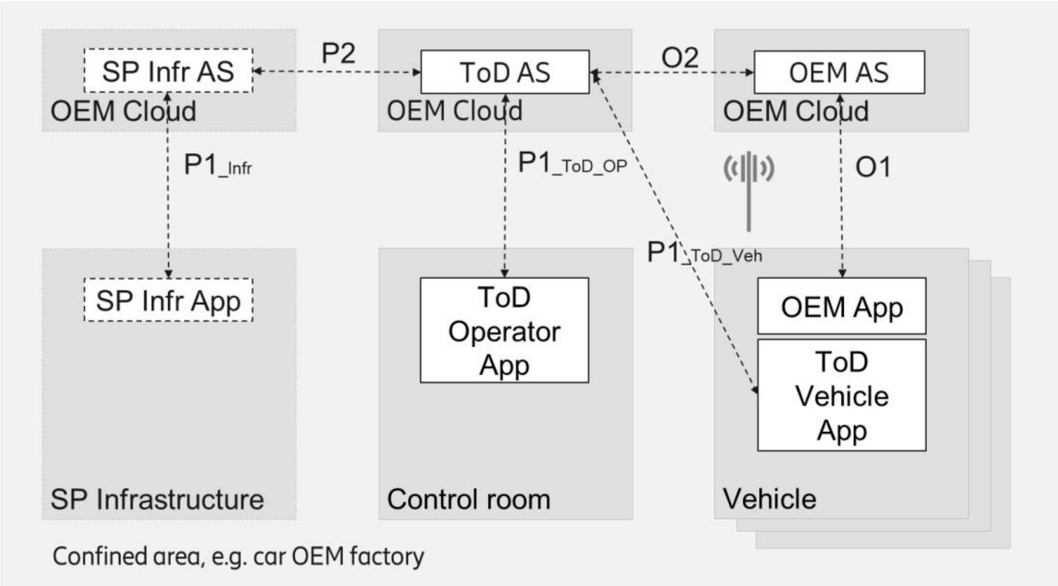

Figure 4: Deployment view of architecture for ToD service in confined areas, e.g. OEM factory (ToD Stage 1)

Table 4: Interfaces in system application layer architecture for ToD in confined areas

Interface	Component 1	Component 2	Data Protocol	Notes
O1	OEM AS	OEM App	Proprietary	
O2	OEM AS	ToD AS	Proprietary	In this scenario, OEM AS, ToD AS and SP Infr AS can all be implemented in the OEM cloud. This interface may be realised as an internal API.
$P1\_{ToD-OP}$	ToD AS	ToD Operator App	Proprietary	The user plane protocol may be from a ToD technology provider.
$P1\_{ToD-Veh}$	ToD AS	ToD Vehicle App	Proprietary	The user plane protocol may be from a ToD technology provider.
P2	ToD AS	SP Infr AS	Proprietary	
$P1\_{Infr}$	SP Infr AS	SP Infr App	Proprietary	

5.2.2.2 ToD for Automated Valet Parking (AVP) service in public garages (example service scenario in ToD Stage 2)

Figure 5 shows the deployment view of ToD architecture for Automated Valet Parking services in public garages, as an sample scenario in ToD Stage 2. Unlike ToD in confined areas, vehicles from different car OEMs may use the ToD service from different AVP Service Providers (garage operators). Cross-OEM and Service Provider interoperability become important for mass deployment of such services. This also raises the need for standardisation or agreement among stakeholders on certain interfaces, as summarised in Table 5.

Communication between vehicles and the OEM cloud and between vehicles and Service Provider systems (garages) can be realised using dedicated cellular networks or public mobile networks from one or multiple MNOs.

Note: This architecture is applicable to Indirect Control ToD and Direct Control ToD services.

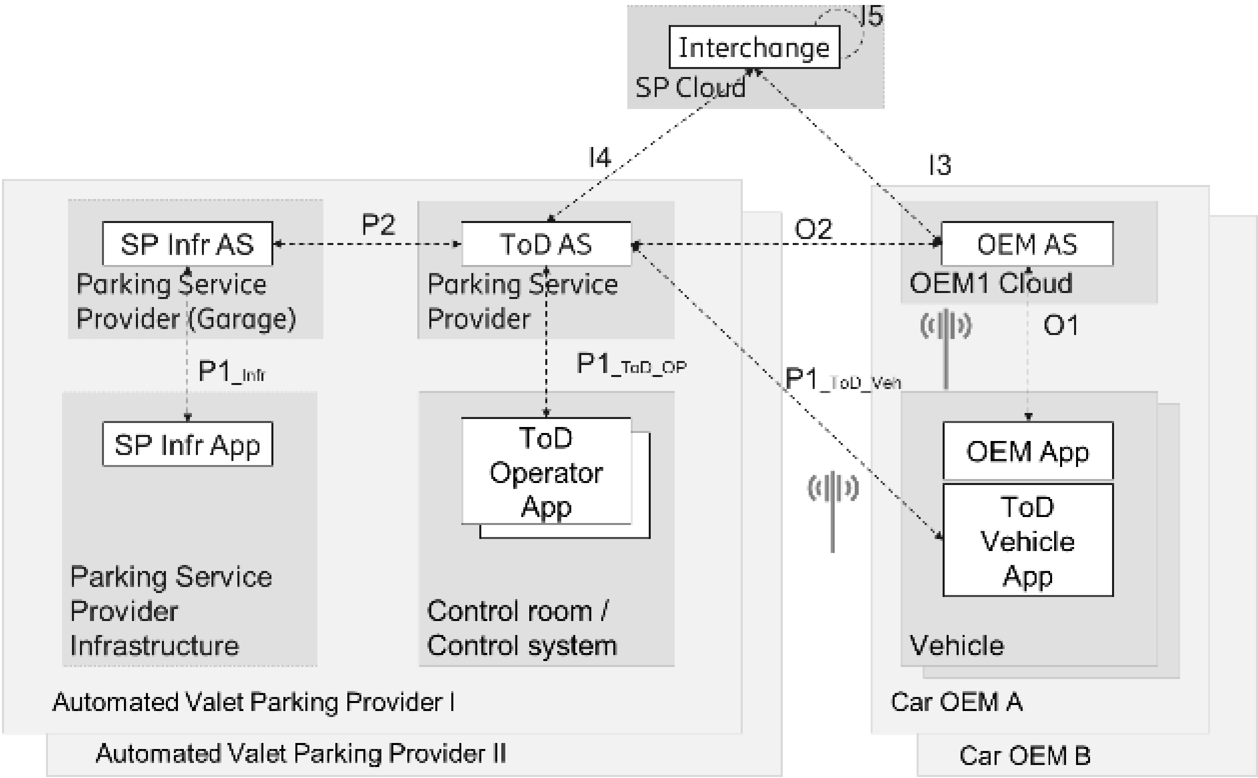

Figure 5: Deployment view of architecture for Automated Valet Parking service in public garages (ToD Stage 2)

Table 5: Interfaces in ToD system application layer architecture for Automated Valet Parking service in public garages

Interface	Component 1	Component 2	Data Protocol	Notes
O1	OEM AS	OEM App	Proprietary	This interface may be reused for other V2N services.
O2	OEM AS	ToD AS	To be standardised or agreed among stakeholders	In this scenario, to enable cross-OEM and Service Provider interoperability for ToD service initiation and configuration, this interface needs to be standardised.
$P1_{\_ToD\text{-}OP}$	ToD AS	ToD Operator App	To be standardised or agreed among stakeholders	To enable cross-OEM and Service Provider interoperability, the user plane protocol between ToD Operator App and ToD Vehicle App needs to be standardised. The exact protocol to be standardised depends on the type of ToD services, whether infrastructure support is used, and whether a human or machine ToD operator is engaged.
$P1_{\_ToD\text{-}Veh}$	ToD AS	ToD Vehicle App	To be standardised or agreed among stakeholders	See notes for $P1_{\_ToD\text{-}OP}$.
P2	ToD AS	SP Infr AS	Proprietary	
$P1_{\_Infr}$	SP Infr AS	SP Infr App	Proprietary	
I3	IF	OEM AS	To be standardised or agreed among stakeholders	This interface enables OEM backend servers to discover AVP Service Providers. For example, AMQP can be used for OEM backend servers to subscribe to service announcement from AVP Service Providers.
I4	IF	ToD AS	To be standardised or agreed among stakeholders	This interface enables Service Providers to announce AVP services. For example, AMQP can be used for Service Providers to publish AVP service announcement.
I5	IF	IF	To be standardised or agreed among stakeholders	This interface enables interconnect of Interchange Functions to improve system scalability. For example, IP-based Interface specified by C-Roads [25] can be used for this interface.

5.2.2.3 ToD services for cross-region mobility (sample service scenario in ToD Stage 3)

Figure 6 shows the deployment view of ToD architecture for cross-region mobility, a scenario of ToD Stage 3. As in the AVP scenario in ToD Stage 2, vehicles from different car OEMs may use the ToD service from different Service Providers. Additionally, vehicles operating on a cross-region corridor may also interact with ToD Service Providers and

RTAs in different regions. Cross-OEM, service provider, and RTA interoperability become important for mass deployment of such services. This also raises the need for standardisation or agreement among stakeholders on certain interfaces, as summarised in Table 6.

Communication between vehicles and the OEM cloud and between vehicles and ToD Service Providers can be realised using public mobile networks from MNOs in different regions with improved network reselection performance at network borders, as studied in section 7.4.1.

Note: This architecture is applicable to both Indirect Control ToD and Direct Control ToD services.

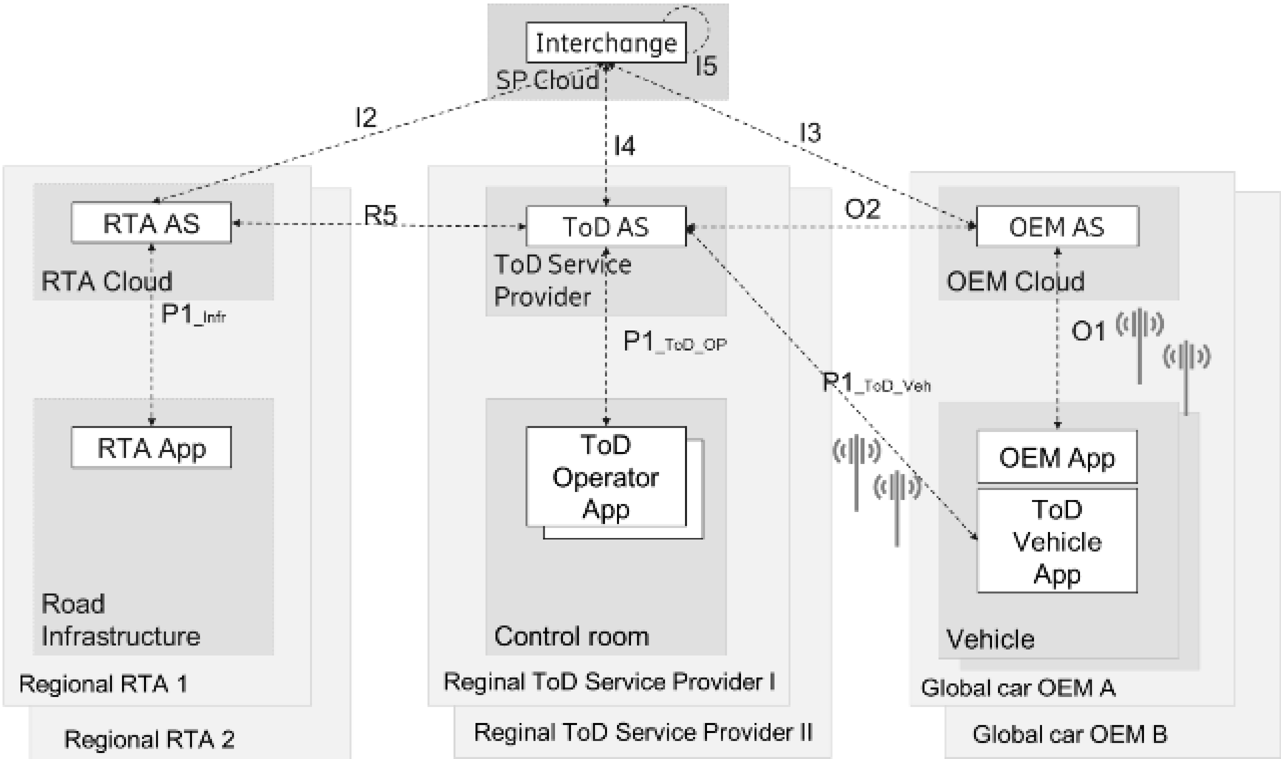

Figure 6: Deployment view of architecture for ToD services for cross-region mobility (ToD Stage 3)

Table 6: Interfaces in system application layer architecture for ToD services for cross-region mobility

Interface	Component 1	Component 2	Data Protocol	Notes
O1	OEM AS	OEM App	Proprietary	This interface can be reused for other V2N services.
O2	OEM AS	ToD AS	To be standardised or agreed among stakeholders	In this scenario, to enable cross-OEM and Service Provider interoperability for ToD service initiation and configuration this interface needs to be standardised.
$P1\_{ToD\text{-}OP}$	ToD AS	ToD Operator App	To be standardised or agreed among stakeholders	To enable cross-OEM and Service Provider interoperability, the user plane protocol between the ToD Operator App and ToD Vehicle App needs to be standardised. The exact protocol to be standardised depends on the type of ToD services, whether infrastructure support is used, and whether a human or machine ToD operator is engaged.
$P1\_{ToD\text{-}Veh}$	ToD AS	ToD Vehicle App	To be standardised or agreed among stakeholders	See notes for $P1\_{ToD\text{-}OP}$.
$P1\_{Infr}$	RTA AS	RTA App	Proprietary	
R5	RTA AS	ToD AS	To be standardised or agreed among stakeholders	To enable cross-SP and RTA interoperability, this interface needs to be standardised. The exact protocols depend on the information exchanged between the RTA AS and ToD AS. Potential ITS information between the RTA and ToD AS include DATEX II, DENM, IVIM, SREM, SSEM, SPATEM, MAPEM.
I2	IF	RTA AS	To be standardised or agreed among stakeholders	This interface enables RTAs to announce ITS services. For example, AMQP can be used for RTA backends to publish ITS information.
I3	IF	OEM AS	To be standardised or agreed among stakeholders	This interface enables OEM backend servers to discover ToD Service Providers and ITS information from RTAs. For example, AMQP can be used for OEM backend servers to subscribe to ToD service announcement.
I4	IF	ToD AS	To be standardised or agreed among stakeholders	This interface enables Service Providers to announce ToD services and discover ITS information from RTAs across regions. For example, AMQP can be used for Service Providers to publish ToD services and subscribe to RTA ITS information.

I5	IF	IF	To be standardised or agreed among stakeholders	This interface boosts the connection betweenInterchange Functions to improve scalability of the system. For example, IP-based Interface specified by C-Roads [25] can be used for this interface.

6 Requirements analysis of ToD system

This chapter analyses technical requirements of the ToD system and sub-systems, i.e. vehicle sub-system, ToD operator sub-system, infrastructure sub-system, and communication networks.

6.1 Functional requirements of vehicle sub-system

Based on ToD Task 1 work, the following requirements have been identified for the vehicle sub-system:

- The vehicle should be able to know its own geographical position and send it to the ToD Service Provider when required.
- The vehicle should be able to calibrate and synchronise the perception sensors and ensure the vehicle sub-system is in a proper state for engaging in the ToD service, especially for a machine ToD operator.
- From a functional safety perspective, the teleoperated vehicle should be able to detect any malfunctioning of the ToD system and override the ToD vehicle sub-system to bring the vehicle to a *minimal risk condition*, e.g. in case of loss of connectivity, intruders to the vehicle, or other fault leading to the creation of faulty actuation data.
- In the event that accurate geographical position is unknown, the teleoperated vehicle that has Dispatch ToD or Indirect Control ToD services engaged, should be able to come to a safe standstill similar to the malfunctioning ToD vehicle sub-system, see section 7.1.2.
- The vehicle may share sensor information with the ToD operator, which may include, among others, video streams from on-board cameras, LiDAR, and RADAR data, as described in section 7.1.
    - Note: C-V2X direct and network communication may be used for additional ‘beyond-LOS’ sensor capability from other vehicles, road infrastructure, or via RTA backends.
- Vehicle sub-systems need to obtain information on service level latency in the current network in order to monitor the latency requirements. The vehicle should be able to verify, change and act on the instructions from the ToD operator according to the acquired latency information.
- Subject to the applicable regulations, the vehicle should be able to store ToD-relevant communication for later evaluation, inspection, and analysis.
- The vehicle should be able to inform the in-vehicle system or user about the operations and status of the ToD operator and system, e.g. whether the ToD operator is engaged in the service.
- When engaged in ToD services, the vehicle sub-system should take steps to protect the ToD system from security threats. Most importantly, it must be ensured that attackers cannot gain control of the vehicle’s movement. [42]

For Indirect Control ToD

- The vehicle should be capable of following remote trajectories, e.g. being capable of and engaging automated driving of Level 4 or higher.

For Direct Control ToD

- The vehicle should be capable of processing remote actuator commands.
- The vehicle should receive from the ToD operator manoeuvre instructions and execute them, according to vehicle’s on-board security checks.
- The vehicle should be able to receive notifications about expected QoS change (i.e. QoS prediction), if such notifications are available, and then appropriate adaptations should be applied (e.g. reduce speed, enable safe operation, etc.)

In ToD Stage 2 and Stage 3 scenarios, e.g. ToD for Automated Valet Parking in public garage, and to enable inter-OEM and Service Provider interoperability, the interface between the ToD Vehicle App on the vehicle side and the ToD Operator App on the ToD operator side needs to be standardised, for both Indirect Control ToD and Direct Control ToD services.

In ToD Stage 2 and Stage 3 scenarios, as with ToD for Automated Valet Parking and ToD for cross-region mobility, vehicles should be able to discover available ToD services matching their needs. This can be done through OEM backends.

6.2 Functional requirements of ToD operator sub-system

Basic functional requirements for ToD operator sub-systems are different for Human Remote Control (HRC) and Machine Remote Control (MRC). Figure 7 illustrates ToD operator sub-systems including both MRC and HRC. The ToD operator sub-system performs the operation for the vehicles via 4G or 5G network connectivity..

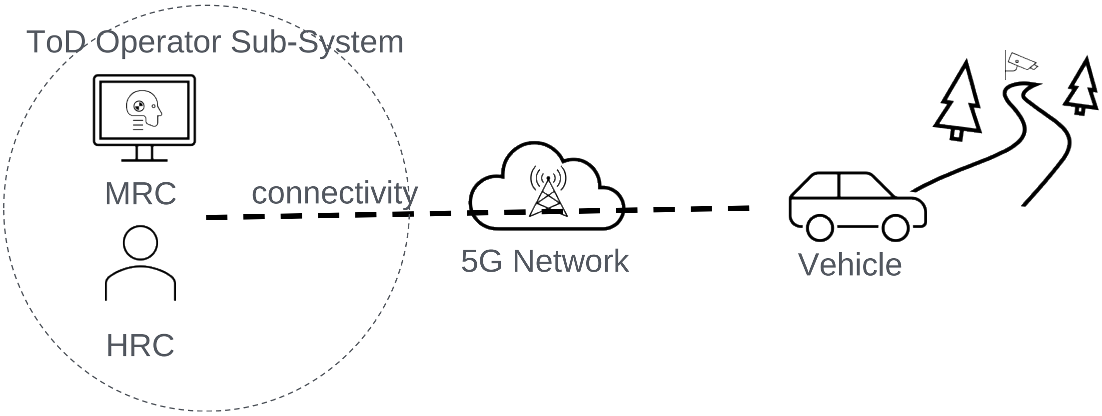

Figure 7: Diagram of ToD operator sub-system

Requirements applicable to both HRC and MRC cases include:

- Requirements related to information and parameters acquiring
    - The ToD operator sub-system should be able to acquire the ToD type, vehicle capability, and ToD related parameters of the vehicle sub-system in a real-time manner.
    - The ToD operator sub-system should be able to detect the malfunctioning of ToD system and bring the vehicle to *a minimal risk condition*.
    - The ToD operator sub-system should be able to detect the exit of ODD and disengage the ToD function in a safe manner.
    - The ToD related parameters and information may be different for Indirect Control ToD and Direct Control ToD.
        - For Indirect Control ToD, the ToD-related parameters include the geographical position of the vehicle and the parameters related to object and events information related to the Dynamic Driving Task (DDT) defined in SAE [19].
        - For Direct Control ToD, in addition to the ToD-related parameters required under Indirect Control conditions, the parameters needed to perform sustained lateral and longitudinal vehicle motion control are needed for the DDT.
    - The ToD operator sub-system should be able to obtain additional sensor data and information, e.g. vehicle status data, road weather conditions and infrastructure data, in order to display it to the ToD operator, to improve the remote driving experience.
- Requirements related to security
    - The ToD operator sub-system should be able to authenticate and authorise the human ToD operator and machine ToD operator apps/entities.
- Requirements related to vehicle control
    - The ToD operator sub-system should be able to send commands to the vehicle for the purpose of remote control for Indirect Control and Direct Control.
    - The ToD operator sub-system should be able to change the ToD Type of the controlled vehicle when needed.
- Requirements related to billing and charging

  - The ToD operator sub-system should support billing and charging which can be a separate function of the ToD operator sub-system.

- Requirements related to connectivity

  - The ToD operator sub-system should be able to monitor the connectivity including notification about QoS performance and expected QoS changes provided by the MNO's network, and should be able to adjust the way the vehicle is controlled depending on the connectivity quality.

For the HRC case, some additional requirements are provided as follows:

  - The ToD operator sub-system should be able to display the ToD Type and ToD-related parameters via the HMI, considering both text and visual forms.

  - The ToD operator sub-system should be able to monitor video signal latency and quality.

  - The ToD operator sub-system should be able to display the real-time video around the vehicle with acceptable user experiences.
  - The remote (human) driver should also be qualified to operate the ToD operator sub-system.

For the MRC case, some additional requirements are provided as follows:

  - The ToD operator sub-system should be able to use recognised objects and digital maps instead of a simple video signal in order to perform the machine-remote operation and the remote-driving algorithm may also need qualification.

To enable end-to-end ToD operations together with other ToD sub-systems, in addition to the latency and data rate requirements discussed in Section 6.5 and 6.6, further HMI sub-system performance requirements need to be defined. These include view angle of video signal, e.g. 150~180 degree, and video signal quality, e.g. in terms of Peak Signal-to-Noise Ratio (PSNR)[6], and granularity of control signal, etc.

6.3 Functional and performance requirements of Infrastructure sub-system

This section describes what Infrastructure sub-systems need to provide additional sensor and communication capabilities. Each form of Tele-Operated Driving requires a high-bandwidth wireless communication link between operator and vehicle for the transmission of video, audio and sensor data. This section does not go into detail about this communication link but describes additional Infrastructure functionality. The purpose of the Infrastructure is to provide environment perception data to either augment the sensor data from the Host Vehilce (HV) or to provide the complete environment model. The infrastructure can operate in either of two modes.

1. Support a human operator
2. Support a machine operator

In the first case, if the HV's sensor data is available a human operator uses it as primary driving input. The infrastructure then provides additional camera perspectives to the operator and can produce safeguards and warnings. Optionally, the human operator can be supported by methods to evaluate the safety of the situation around the HV based on the distance, direction and speed of other traffic participants. One example of this is so-called Responsibility Sensitive Safety (RSS) [40] by Mobileye.

If only infrastructure sensors are available, it is not possible to provide a real-time video feed from the drivers' perspective because infrastructure sensors look at the HV from the outside. Therefore, simulated input comparable to a video game is provided as the main operator's view. Simulated means computer-generated based on object and map information. The computer uses all available sensor input and state-of-the-art object classification and detection methods to generate a 3D model of the environment. The computer then projects a 'viewpoint' into that scene as a driver inside the HV would perceive it. 3D rendering techniques known from video games can be used for that purpose. In addition, 'real video' data from the Infrastructure's perspective will also be provided to the human operator as is to verify the computer-generated environment.

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[6] A reference calculation method of PSNR can be found at https://www.mathworks.com/help/vision/ref/psnr.html.

In contrast, a machine operator uses software architecture for automated driving similar to that of an automated vehicle. The main functional blocks like perception, environment modelling and planning are present in the Infrastructure.

In both cases, the requirements vis-a-vis the Infrastructure's perception components are:

1. Provide a complete, accurate and timely environment model for the road and all vehicles and pedestrians: the environment model contains Location, Type, Direction, Speed and Dimensions for each traffic participant or obstacle.
2. Cover the complete path from the HV's current position to its ToD destination with additional field of vision to the front, back and the sides. Again, RSS can be used to calculate appropriate field-of-view depending on the type of road.

Multiple sensors are required to achieve the above requirements. From a safety perspective, perception inputs from different types of sensors are required. For the time being, video cameras and RADAR sensors are considered as the minimal setup for sensor perception related to Infrastructure. Video cameras are suitable for object classification and detection while RADAR sensors are suited to detecting distance and the speed of objects. Experience in current test-beds suggest that other sensor types can be added for greater reliability in poor light and weather conditions. Event cameras can augment video cameras during night-time driving or bad weather conditions. LiDAR sensors provide good distance and free space measurements.

Sensors must be positioned at the right height and on all sides of the drivable path in order to prevent occlusions or disrupted views. In fact, for situations where only Infrastructure sensors are available, it must be ensured that no blind spots exist. C-V2X Infrastructure can be very useful for this, e.g. RSUs along the drive path can send C-V2X messages received from nearby vehicles to augment sensor data from fixed positions. Sensor data must be properly calibrated and synchronised, or use the same time and space base, meaning that sensor recordings require precise timestamps in the millisecond range in order to generate high-quality sensor fusion results.

In addition to the sensors themselves, sufficient computing resources are required at the edge, close to the sensors. In particular, video data must be processed on-site to reduce overall latency. The 'edge compute' platform has the task to create an environment model out of the sensor data using machine-learning and other computationally intensive algorithms. When machine operated, the respective algorithms will use the environment model to drive the HV. In order to achieve low latency, it is recommended that the machine operator works with the edge platform as well. When a human operator is involved, a high-bandwidth data connection is required to transmit the environment model to the human driver. The computer-generated representation (reconstruction) of the real environment can happen both at the edge or at the operator's site.

Infrastructure used for ToD tasks is safety critical and must be protected against malicious activities. One of the most critical aspects is to uphold the integrity and availability of sensor data to provide timely, accurate and complete information about the environment for both machine and human operators. Some forms of attack include physical destruction, disconnection or misalignment of sensors, interruption of communication channels or faking, modifying or replaying sensor data, as well as the traditional threats related to unauthorised access to the platform.

Security measures need to be added to ensure the availability, integrity and accuracy of all data channels, from the sensor to the edge, from the edge to a human operator and back, as well as between the edge and the vehicle. In addition, the edge server itself needs to be protected against malicious access.

Additional monitors validating the safe operation of each system component are required. If needed, these monitors can fully or partially disable the functionality of the Infrastructure-supported ToD and properly communicate such changes with the corresponding vehicle services. This is the equivalent to switching an automatic vehicle into a safe state.

Table 15 in Annex A lists quantitative service level requirements (SLR) of Infrastructure-based Tele-Operated Driving use case defined in [5].

6.4 Functional and performance requirements of communication network

Based on the work in Task 1 of the ToD XWI, the following functional requirements are identified for communication networks:

- The ToD operator should establish a mutually authenticated and secure communication session with the vehicle.
- Service continuity should be guaranteed during the operation of ToD service. (See Section 6.5 and 6.6 for discussion on latency and reliability requirements.)

- The communication link should be reliable and encrypted. (See Section 6.6 for discussion on reliability requirements.)
- For the best availability of ToD services, the communication session fulfilling the latency and reliability requirements should be maintained, i.e. when the vehicle drives through national borders or needs to roam between different MNOs or operate under different RTAs or in different geographical regions. In the event that the latency and reliability requirements cannot be guaranteed in cross-border environments, the ToD operator and the vehicle should be informed in advance.
- The network should be able to send notifications about expected QoS changes (i.e. QoS prediction) to vehicles and the ToD operator, if such notifications are available.
- The communication network side should make the measured latency information available to the vehicle and the ToD operator.

The communication network supporting ToD services should fulfil the communication latency requirements identified in Section 6.5. Note: The definition and composition of service level latency are provided in subsection 6.5.1.

The communication network supporting ToD services should fulfil the communication capacity and reliability requirements identified in Section 6.6.

6.5 Latency requirements of ToD services

This subsection investigates the end-to-end latency requirements of ToD services, considering different use cases and scenarios, as well as vehicle speed and types of ToD operation.

6.5.1 Definition and composition of service level latency requirement

5GAA WG1 [5] defines service level latency as: *measurements of time from the occurrence of the event in scenario application zone to the beginning of the resulting actuation. Depending on implementation, this includes one or more of following:*

- *processing of the event into information by the information generator,*
- *communication of the information to end-user,*
- *processing of the information by the end-user and*
- *time to actuation driven by the result of processing of the information*.

Figure 8 and Figure 9 illustrate the latency composition of ToD service operation in uplink (from the host vehicle to the ToD operator) and downlink (from ToD operator to host vehicle), respectively.

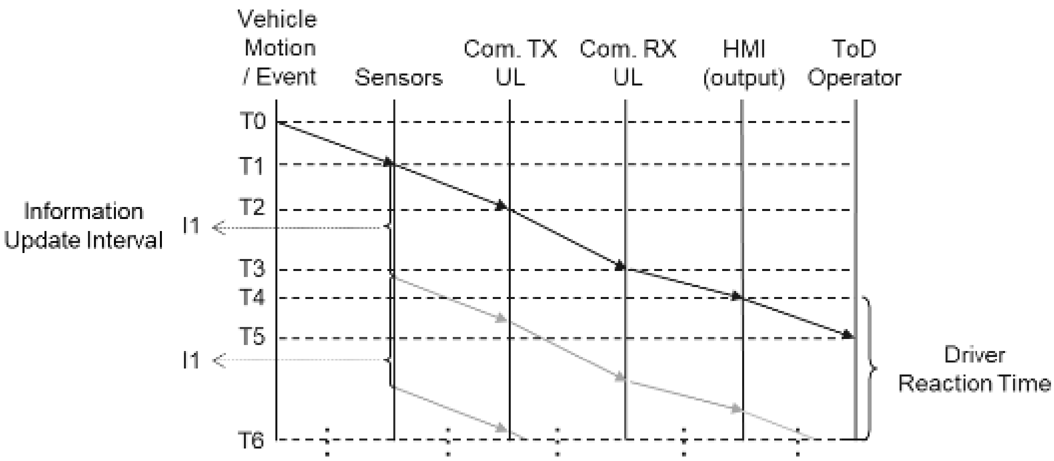

Figure 8: Latency composition of ToD service in uplink (host vehicle to ToD operator)

Reference time points for analysing the composition of uplink latency are:

- T0: the time point when the event occurs
- T1: the time point when the raw data about the event are acquired by the sensors

- T2: the time point when the communication protocol layer 2 SDU packet containing information of the event is ready for transmission at or within the vehicle's communication unit
- T3: the time point when the communication protocol layer 2 SDU packet is received by the communication unit on the ToD operator side
- T4: the time point when the information about the event reaches the HMI output (ToD operator side)
- T5: the time point when the ToD operator perceives the information
- T6: the time point when the ToD operator acts, e.g. moves his/her hand in response to the perceived event

The components of ToD uplink latency, delimited using the reference time points in Figure 8, are:

- T1-T0: the latency for vehicle sensors to acquire data about the vehicle motion or an event, including the sampling latency of sensors
- T2-T1: the latency for preparing data packets on the vehicle side, including data encoding and compression delay (if applicable), communication latency in the vehicle, and other processing time, e.g. security etc.
- T3-T2: the latency for communication from the vehicle towards the ToD operator, including communication latency of the mobile network and backend systems
- T4-T3: the latency for ToD Operator App to process and present the received information, including decoding, buffering, displaying and other processing time, e.g. security
- T6 –T4: the driver 'reaction time'[7] (ToD operator side) which is usually set at 1 second level[8] for human drivers

The vehicle periodically acquires, processes, and sends information to the ToD operator. I1 in the figure denotes the Information Update Interval of sensors, which can be determined by the frame rate of a camera or the sampling rate of a sensor.

In this study, (T3-T2) is referred to as **uplink communication latency**. (T2-T0) + (T4-T3) is collectively referred to as **uplink application latency**.

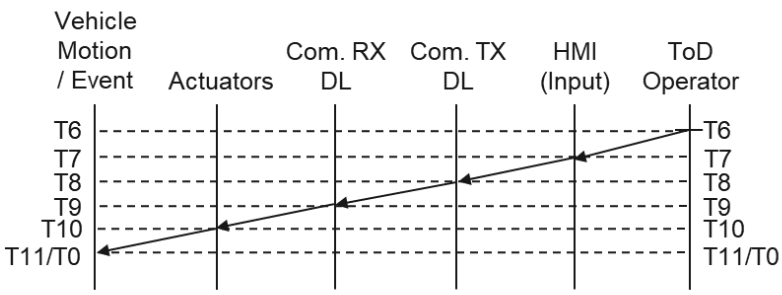

Figure 9: Latency composition of ToD service in downlink (from ToD Operator the host vehicle)

Reference time points for analysing the composition of downlink latency are:

- T6: the time point when the ToD operator acts, e.g. when the ToD operator moves his/her hand
- T7: the time point when the manoeuvre command from the ToD operator is captured by the HMI input device
- T8: the time point when the communication protocol layer 2 SDU packet of the manoeuvre command is ready for transmission at or within the communication unit of the ToD operator
- T9: the time point when the communication protocol layer 2 SDU packet of the manoeuvre command is received by the communication unit on the vehicle side
- T10: the time point when the actuators receive the manoeuvre command from the ToD operator
- T11: the time point when the vehicle motion occurs as the consequence of the manoeuvre command
    - o Note: T11 overlaps with T0 of the next uplink process

[7] See Clause 6.4.2 in SAE J2944 OPERATIONAL DEFINITIONS OF DRIVING PERFORMANCE MEASURES AND STATISTICS for the definition of Reaction Time.

[8] See Heikki Summala, Brake Reaction Times and Driver Behavior Analysis, TRANSPORTATION HUMAN FACTORS, 2(3), 217–226, 2020

The components of ToD downlink latency, delimited using the reference time points in Figure 9, are:

- T7-T6: the latency for input devices to capture the manoeuvre command from the ToD operator, including the sampling latency of the input devices
- T8-T7: the latency for the ToD operator app to prepare the data packet, including time for data encoding, compression (if applicable), and other processing, e.g. security
- T9-T8: the latency for communication from the ToD operator app to the vehicle, including communication the latency of backend systems and mobile networks
- T10-T9 the latency for the ToD vehicle app to process the received manoeuvre command from the ToD operator, including time for data decoding, decompressing (if applicable), and other processing, e.g. security
- T11-T10 the latency for vehicle actuators to execute the manoeuvre command from the ToD operator, including the latency of actuators

In this study, (T9-T8) is referred to as **downlink communication latency**. (T8-T6) + (T11-T9) is collectively referred to as **downlink application latency**.

6.5.2 Latency requirement values of ToD services from previous studies and research projects

6.5.2.1 Latency requirement values from 5GAA WG1 [5]

5GAA WG1 has provided among other service level requirements the values of service level latency requirement for ToD use cases in [5]. The service level latency requirement values in [5] have been derived at the service level for given maximum vehicle speeds. For example, the service level latency requirements of ToD Support use case is given in [5]*:*

For the Tele-operated Driving use case (vehicle speed up to 50 km/h):

Service level latency	[ms]	From HV to ToD operator: 100 From ToD operator to HV: 20	From ToD operator to HV: Depends on the reaction time[9] needed, which is directly related to the maximum driving speed allowed. For instance, at a speed of 50 km/h, the HV will move 0.27 m within 20 ms.

For user story #1 of Tele-Operated Driving Support: Remote Steering (Direct Control ToD, vehicle speed up to 10 km/h)

Service level latency	[ms]	From HV to ToD operator: 100 From ToD operator to HV: 20	From ToD operator to HV: Depends on the reaction time needed, which is directly related to the maximum driving speed allowed.

For user story #2 of Tele-Operated Driving Support: Remote Driving Instructions (Indirect Control ToD, vehicle speed up to 10 km/h)

Service level latency	[ms]	From HV to ToD operator: 100 From ToD operator to HV: 200	From ToD operator to HV: With only the instructions to be transmitted from ToD operator to the HV, latency requirements are more relaxed.

Note: For Indirect Control ToD, the latency depends on the time the user has to decide for the Indirect Control to take effect, and on the type of control information, e.g. continuous Indirect Control with way points or decision in a dead lock situation. In a dead lock situation, the ToD operator may not be able to decide within the usual reaction time, thus the service level latency is even more relaxed.

[9] ‘Reaction time’ refers to the time from the moment that a ‘driving command’ is decided by the remote driver and is received by the vehicle.

6.5.2.2 Latency requirements from 5GCroCo project

5GCroCo ToD use case is defined as the remote control of automated vehicles by a human over mobile radio networks, within one country and across borders. It is meant to complement automated driving by bringing the tele-operator, located in the vehicle control centre (VCoC), into the control loop in situations that an automated vehicle cannot handle. Therefore, this concept utilises the strength of human beings to handle complex scenarios. The vehicle, provided with automated and ToD functions, is transmitting to and receiving data from the VCoC via the mobile 5G network.

Several user stories have been specified in the 5GCroCo project. The corresponding SLRs are analysed in [6] [38]. User story 1 and 2 investigate Direct Control ToD and Indirect Control:

User Story 1 – Remotely Controlled Manoeuvring (Direct Control ToD, vehicle speed < 15km/h): The goal of the test cases for this user story is to demonstrate how tele-operated driving and 5G communication technology can be used to overcome scenarios in which an automated driving (AD) vehicle does not know how to handle an unexpected road blockage.

KPI Title	KPI Unit	KPI Value
Range	[m]	Manoeuvring range: < 100 m Service range: > 10 km
Information exchanged and estimated payload	[bit/s]	Uplink: 10-50 Mbit/s Downlink: max. 500 kbit/s
Network latency (from the application in the vehicle to the application in the VCoC	[ms]	40 ms
Service level reliability	[%]	Uplink: 99 % Downlink: 99.9 %
Maximum age of information[10]	[ms]	150 ms

User Story 2 – Remotely Controlled Path-based Driving (Indirect Control ToD, vehicle speed < 15 km/h): Similar to user story 1, the goals of the test cases for this user story are to demonstrate how ToD and 5G communication technology can be used to overcome scenarios in which an AD vehicle does not know how to tackle an unexpected road blockage. In this user story, the Indirect Control concept, which is less critical in terms of latency, is applied.

KPI Title	KPI Unit	KPI Value
Range	[m]	Manoeuvring range: < 100 m Service range: > 10 km
Information exchanged and estimated payload	[bit/s]	Uplink: 8-30 Mbit/s Downlink: max. 300 kbit/s
Network latency (from the application in the vehicle to the application in the VCoC)	[ms]	80 ms
Service level reliability	[%]	UL: 99 %

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[10] Maximum age of information is defined in D2.1 of 5GCroCo [6]: "The maximum age of information, displayed in the VCoC, needs to facilitate an appropriate reaction time of the tele-operator to the current situation. Extending the KPI of the service level latency, the update rates of the sensors of the vehicle and state feedback need to be considered for the maximum age of the information. It can be understood as the end-to-end latency it takes from an event in front of the camera sensor on the vehicle to be displayed to the tele-operator in the vehicle control centre." This definition corresponding to (T4-T0) is in Figure 8 of the present document.

		DL: 99.9 %
Maximum age of information[10]	[ms]	300 ms
Positioning accuracy	[m]	0.5 m
Deviation of desired trajectory	[m] [deg]	+/- 0.3 m +/- 5 deg

The 5GCoCo project also investigates remote driving scenarios with less demanding UL configurations, for situations of low QoS or to reduce uplink bandwidth requirements [6][38].

6.5.2.3 Latency requirements from 5GMobix project

5G-MOBIX project includes a ToD use case for an automated tourist bus that can be controlled remotely by one operator in case the vehicle enters a roadblock or blocking scenario requiring human intervention. The ToD operator will take remote control of the vehicle in this case, to provide support without needing an operator on-site.

For ToDriving use case (vehicle speed up to 8 km/h):

Service level latency	[ms]	From camera capture to ToD operator display: 120 ms. Uplink latency From remote control gears to the Host Vehicle: 80 ms. Downlink latency	From ToD operator to HV: Depends on the reaction time needed, which is directly related to the maximum driving speed allowed. For instance, at a speed of 8 km/h, the HV will move 0.44 m within 200 ms.

This 200 ms total latency is the worst-case scenario for the video feed uplink plus the control command latency from the ToD operator to the HV. In the event that this application end-to-end latency is greater than 200 ms the vehicle must reduce the maximum speed of 8 km/h or fully stop until the system can guarantee the required latency. Deviation is the vehicle maximum distance that the vehicle moves until the ToD operator command is executed in the car, including video latency and the human factor. This maximum distance is correlated with the precision operation of the vehicle.

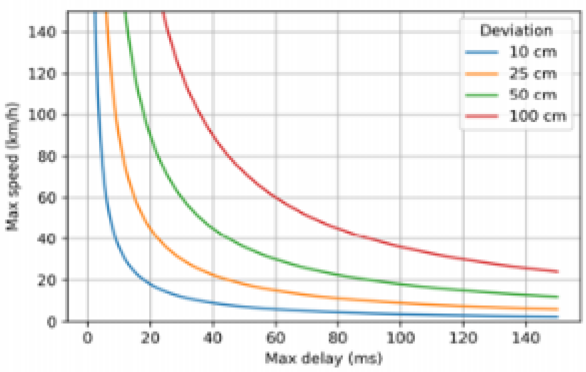

Figure 10: Maximum speed vs. maximum delay for given maximum deviation

In the 5G-MOBIX project, the quality of the video is also relevant for the ToD operator, so the codec will also be key for the service quality. The following picture shows the relationship between the video bit-rate and its perceived subjective quality, i.e. Mean Opinion Score (MOS).

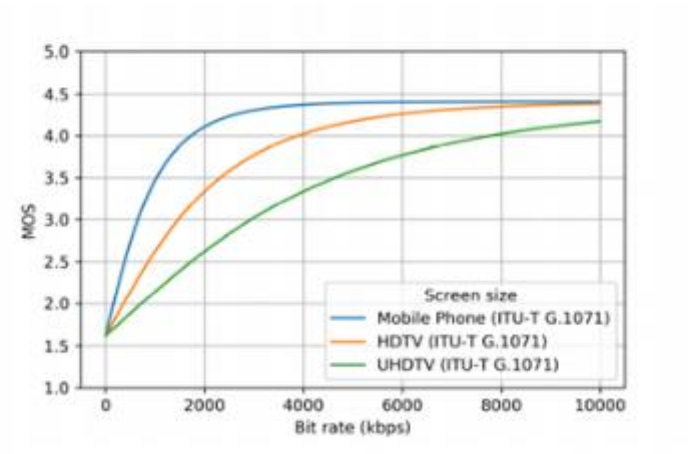

Figure 11: Video MOS vs encoding bit-rate

Video MOS depends also on the visual usability of the content, in the following picture we can see that for the same MOS the required bit-rate for driving, parking or supervision is not the same.

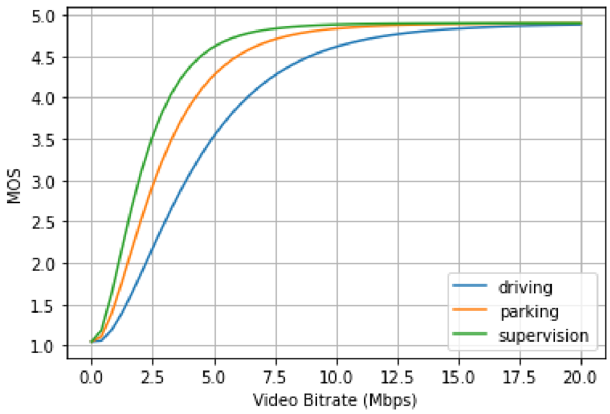

Figure 12: Video MOS vs. encoding bit-rate for ToD driving, ToD parking or supervision

In the 5G-MOBIX project, we have identified a latency characterisation for end-to-end remote control that is explained in the formula presented in $Latency = Tc + Te + Lr + \left(\frac{Be}{Bt}\right) * \left(\frac{1}{Fps}\right) * 1000 + Td + Tr + Th + Txl + Txr$

Figure 14).

The formula includes references to video encoding bit-rate parameters, network round trip (including uplink packet latency and downlink packet latency), bandwidth for the transmission, frames per second, delay for sensors in the car, or in the remote cockpit.

Description	Variable Name
Time to capture one video frame	Tc
Time to encode one video frame	Te
E2E Latency round trip	Lr
Transmission delay	(Be/Bt)*(1/Fps)*1000
Time to decode one video frame	Td
Time to render one video frame	Tr
Human factor	Th
Car command exec delay	Txl
Cockpit sensing delay	Txr
Encoded video bitrate	Be
Transmission bitrate	Bt
Encoded Video Frames per Second	Fps
Latency for Uplink channel	Uplink latency
Latency for Downlink channel	Downlink latency
Total latency	Latency

Figure 13: Latency characterisation parameters

Depending on these parameters, the end-to-end latency is calculated and with the maximum tolerated deviation and vehicle speed we can derive other maximum parameters. As most of these parameters are fixed for a given network scenario and for a given ToD operator and Host Vehicle, we can fine-tune the network for better performance.

$$Latency = Tc + Te + Lr + \left(\frac{Be}{Bt}\right) * \left(\frac{1}{Fps}\right) * 1000 + Td + Tr + Th + Txl + Txr$$

Figure 14: Latency characterisation formula [8]

The 5G-MOBIX project has selected 60 fps cameras, so Fps = 60. The selected encoders have 2 frames delay as Te, so the Te = 2 * (1000/60) = 33.3 ms. The Time to capture is ½ frames, so Tc = 8.33 ms. The uplink latency is about 40 ms and the downlink latency is about 25 ms, so the Lr = 40+25 = 65 ms. The time to decode is 10 ms and the time to render is 5 ms, so this value is Td = 10 Tr = 5 ms. The human factor is assumed to be Th=20 ms, for a well-trained operator and the sensors delays in the car is 10 ms and in the cockpit 40 ms. So Txl = 10 and Txr = 40 ms. The encoded video bit-rate is 20 Mbps, so Be = 20 Mbps, and the transmission bit-rate is 60 Mbps, so Bt = 60 Mbps.

A ToD operator display differs to real vision in the frequency of the visual pictures, we have included a latency value for this new ToD operator display impact. As explained in this 'Time Slices: What Is the Duration of a Percept?'[11] article, the temporal resolution of sensory systems depends on several factors. First, the physical signal of a sensory stimulus needs to be converted into a brain signal. The visual system relies on electrochemical transduction (i.e., light energy causes a change in the protein rhodopsin in the retina), whereas in the auditory and somatosensory systems, sound vibrations or touch are mechanically converted into electrical signals. Second, the signal within the sensory system has to be processed such that changes between stimuli can be detected. Several sensory types of temporal resolution can be distinguished, we have included in the formula the ability to discriminate the repetition of a periodical visual signal. For trains of stimuli, the presentation rate at which the sensation of flicker ceases is similar for the visual and auditory systems, i.e., at around 16 ms inter-stimulus-interval (ISI). We round the ISI to 20 ms.

[11] "Time Slices: What Is the Duration of a Percept?" 2016 Apr; 14(4): e1002433. Published online 2016 Apr 12. doi: 10.1371/journal.pbio.1002433. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4829156/ PLoS Biol. Michael H. Herzog, Thomas Kammer, and Frank Scharnowski

Description	Variable Name	Value in milliseconds
Time to capture one video frame	Tc	8.33
Time to encode one video frame	Te	33.33
E2E Latency round trip	Lr	65.00
Transmission delay	(Be/Bt)*(1/Fps)*1000	5.56
Time to decode one video frame	Td	10.00
Time to render one video frame	Tr	5.00
Human factor	Th	20.00
Car command exec delay	Txl	10.00
Cockpit sensing delay	Txr	40.00
Encoded video bitrate	Be	20.00
Transmission bitrate	Bt	60.00
Encoded Video Frames per Second	Fps	60.00
Latency for Uplink channel	Uplink latency	40.00
Latency for Downlink channel	Downlink latency	25.00
Total latency	Latency	197.22

Figure 15: Latency characterisation parameter values

With these values as example the following formula:

$$Latency = Tc + Te + Lr + \left(\frac{Be}{Bt}\right) * \left(\frac{1}{Fps}\right) * 1000 + Td + Tr + Th + Txl + Txr$$

The Latency is calculated as

$$Latency = 8.33 + 33.3 + 65 + \left(\frac{20}{60}\right) * \left(\frac{1}{60}\right) * 1000 + 10 + 5 + 20 + 10 + 40 = 197.20\ ms$$

In the following picture we have a graphical representation of the latency for the 5G-MOBIX use case, where different contributions to the end-to-end latency are shown. The 65 ms of network latency only represents one third of the total latency budget for the ToD use case.

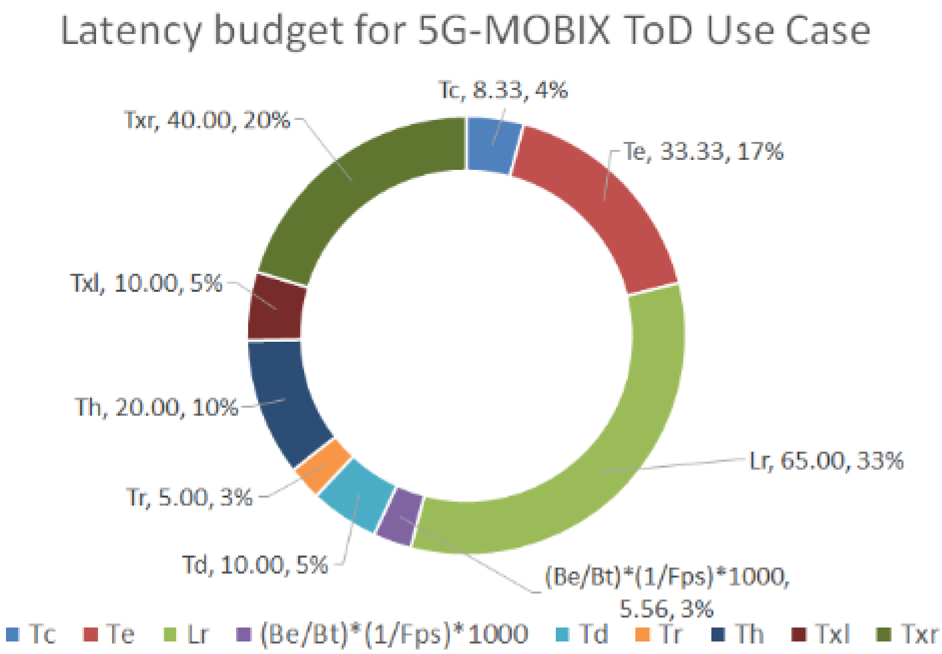

Figure 16: Latency budget example for reference 5G-MOBIX use case

These values can be tweaked depending on implementation optimisations, or network fine-tuning. Depending on how congested the network is, or the car modem prioritisation, the network delay can be minimised.

6.5.3 ToD latency values from field tests

6.5.3.1 Field experiments from [7]

Simulation studies and field experiments in [7] investigated the impacts from communication latency and packet losses to Direct Control ToD. The results reveal that good path following with vehicle speed of 60 km/h is achieved for experimental Direct Control ToD trials exposed to 50 ms or less round-trip communication latency, i.e. sum of uplink communication latency and uplink communication latency defined in Section 6.5.1.

6.5.3.2 Reference values from RoboAuto[12]:

The reference system setup consists of a remote station for the operator and an on-board unit to be installed in the target vehicle. The reference setup optimises the balance between cost and performance while guaranteeing a smooth and safe tele-operation experience. This setup has been successfully used in passenger cars with speeds surpassing 50 km/h. The technical performance of this reference setup in terms of latency is 145 ms glass-to-glass (G2G) latency, meaning the latency from the glass of the camera to the glass of the ToD operator’s screen. This corresponds with the uplink latency from T1 to T4. In the other direction, the control commands being sent to the vehicle are characterised by a driving input delay of 20 ms. This corresponds with the downlink latency from T6 to T10.

Note that these are not strict latency requirements, but performance characteristics of a working and validated ToD solution. This suggests that for a similar ODD (passenger car with speed surpassing 50 km/h) the ToD latency requirements should not be defined more stringently than these values. The system may work with more relaxed values. However, since these values are already achievable on a 4G network, there is no clear indicator for investigating the relaxation of these requirements, i.e. 145 ms max latency from T1 to T4, and 20 ms from T6 to T10.

Table 7: Summary of measured latency values from ToD tests

Source	Use Cases	Service Level Latency Requirements	Communication Latency Uplink	Communication latency Downlink
RoboAuto	ToD measurement (speed 50 km/h)	165 ms (145 ms for uplink, 20 ms for downlink)	45 ms	15 ms
Bennett2020 [7]	Direct Control ToD field test (speed 60 km/h)	Unknown	Round trip communication latency: 50 ms	

6.5.3.3 Impact of latency on trajectory deviation at different speeds in 5G-MOBIX

In order to evaluate the real impact of latency in a real driving experience at a given speed, in the 5G-MOBIX project some remote operators carried out a driving experiment on a circuit at different speeds with several artificially controlled latencies. This exercise helped to evaluate the deviation trajectories and understand what can be considered a secure environment for remote driving. In the project, the real trajectories of the vehicles were recorded with RTK GPS tracking and videos recorded at a real circuit with video drones, to investigate the impact of latency on driving safety and its dependence on the vehicle speed. Figure 17 is a screenshot from the video record of this experiment [41], which shows that with artificially introduced 50 ms latency the driver correctly navigated the curve at a speed of 5km/h. However, when the latency increased to 150 ms and the vehicle speed increased to 15 km/h, the driver the driver had to take the curve wider.

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[12] RoboAuto is a company specialised in enabling companies to remotely control their devices and vehicles (https://www.roboauto.tech/).

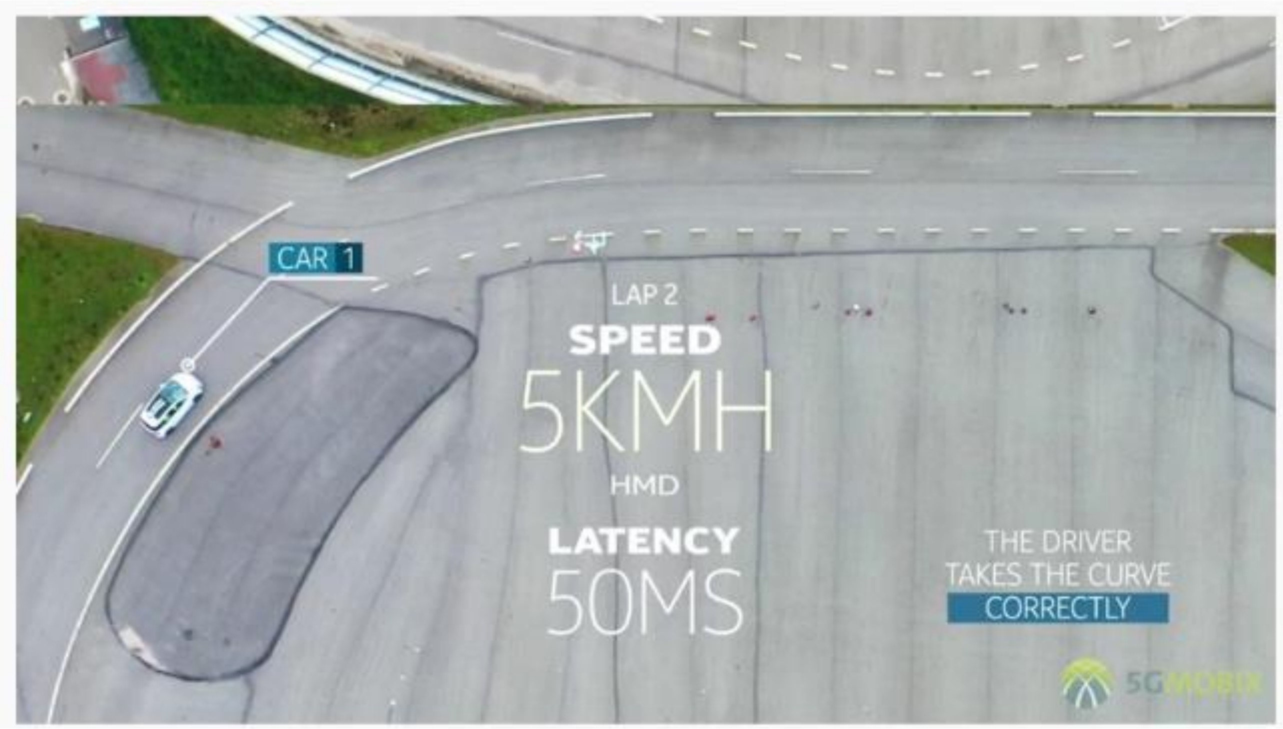


Figure 17: ToD driving trajectory deviation with 50 ms latency in 5G-MOBIX: picture from drone

6.5.4 Discussions

6.5.4.1 Latency for application and communication parts

Field test results in [7] show that 50 ms round-trip communication latency, i.e. sum of uplink communication latency and uplink communication latency, can ensure good Direct Control ToD performance with a vehicle speed up to 60 km/h, though the application latency values on the vehicle and ToD operator sides are unknown.

From the measurement results by RoboAuto for vehicle speeds of 50 km/h, the uplink communication latency is around 45 ms for the image stream from vehicle transceiver to ToD operator receiver, and around 100 ms from the application part in the uplink, though these are very indicative figures.

6.5.4.2 Latency of uplink and downlink

As shown in the latency composition analysis and field test in [7], ToD operation is impacted by the overall round trip latency. Therefore, there is no need to impose separate latency requirements for up- or downlink, as far as the overall round-trip latency fulfils the service level requirement.

Though values from RoboAuto do not indicate uplink or downlink latency requirement separately, being based on an actual product, those values do give a clear indication of the uneven distribution of the latency budget across the uplink and downlink paths. This can be explained, as more components contribute to the uplink G2G latency, e.g. video encoding and decoding, response time of the operator monitor, etc. Additionally, the design of current cellular networks typically provides more downlink capacity than uplink capacity to UEs. Therefore, it is reasonable to reflect this uneven distribution in the definition of latency requirements.

As discussed in Section 6.6, the uplink traffic of ToD use cases is mainly the video feeds for the ToD operators, plus some sensor metrics, resulting in high bandwidth demand in the uplink. Data traffic load in the downlink is relatively low and includes, for example, the control commands from the ToD operator to the car. In this case, the car antenna will be key in order to maximise the channel performance for uplink communication.

6.5.4.3 Latency requirement values and vehicle speed

The vehicle's speed is critical for latency requirements and has impacts on ToD operation in the following subjects, as investigated in the 5G-MOBIX project:

- Vehicles may experience frequent handovers in 5G networks. Thus, the handover procedure must be optimised accordingly and in line with the required maximum latency.
- Maintaining vehicle control precision is more challenging at higher vehicle speeds. Therefore, lower network latency is needed. Figure 10 shows the maximum speed vs. the maximum delay for a given deviation. Deviation is the maximum distance (deviation) that the vehicle moves until the ToD operator command is executed in the car, considering video latency and human factors. This maximum distance is correlated with precision operation of the vehicle.

The video end-to-end latency (visual reality to final operator display latency) has an impact on the perceived video quality by the ToD operators, but the impact also depends on the different uses of the video. Figure 18 shows that the Mean Opinion Score (MOS) is clearly divergent when the operator is driving (Direct Control ToD), parking (Direct Control ToD), or supervising the driving (Indirect Control ToD). For the same latency value, e.g. 300 ms, the ToD operator who is only supervising a vehicle may give a higher MOS value than the ToD operator who is remotely driving the vehicle.

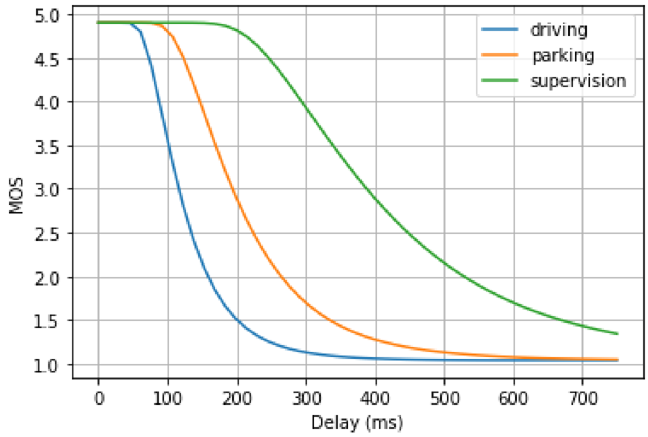


Figure 18: Video MOS vs. end-to-end video delay

6.5.4.4 Exposure of latency information to ToD application

The vehicle sub-system needs to obtain information on service level latency in the current network to monitor the above latency requirements. As an example, it is desirable for the ToD application to know at least the time it takes from T10 to T6, when the actuators execute an operating command at T10. In particular, the information about the downlink communication latency section is important. Alternatively, it is also preferable to acquire the times T1 to T10 by associating the uplink information with the downlink information generated during the uplink. This makes it possible to determine whether the latency requirements are met, as specified in Section 6.5.

The vehicle can change and act on the instructions received from the ToD operator according to the acquired latency information. Furthermore, the ToD operation may be interrupted, in the event that the latency requirement is exceeded. To this end, the communication network is expected to share the measured latency information with the vehicle in the area that the ToD is engaged.

6.5.5 Summary

ToD services are sensitive to the E2E service level latency consisting of both application latency and communication latency. Service level latency requirement values depend on the type of ToD use case, e.g. Direct Control ToD or Indirect Control ToD, and the speed of the vehicle being remotely operated. Direct Control ToD and higher vehicle speed have more stringent service level latency requirement than Indirect Control ToD and lower vehicle speed. The overall 120 ms round-trip service level latency requirement from 5GAA WG1 [5], i.e. 100 ms for the HV to ToD operator (uplink) and 20 ms for the ToD operator to HV (downlink), considers Direct Control ToD with a maximum vehicle speed 50 km/h. For Indirect Control ToD, 5GAA WG1 [5] requires overall 300 ms round-trip service level latency, i.e. 100 ms from the HV to ToD operator and 200 ms from the ToD operator to HV.

As ToD operation is impacted by the overall service level round-trip latency, there is no need to impose separate latency requirements for uplink and downlink, as the overall round-trip latency fulfils the service level requirement. However, uneven distribution of the latency budget across the uplink and downlink paths is observed in practice. As more components contribute to the uplink G2G latency, e.g. video encoding/decoding, the response time of the operator monitor, and the current cellular network design typically provide UEs more capacity for downlink than for uplink. It is considered suitable to reflect this uneven distribution between uplink and downlink when describing ToD latency requirements.

Observations based on field tests and a literature survey [2] show that round-trip communication (network portion) latency of around 50 ms to 60 ms can support Direct Control ToD operation with a vehicle speed of up to 50 km/h.

Note that for ToD services requiring conversational voice communication between the in-vehicle user and the ToD operator, the communication network should meet the latency requirement of 100 ms, as indicated by 5QI 1 in Table 16.

6.6 Data rate requirements of ToD services

6.6.1 Data rate and reliability requirements

This section discusses data rate and reliability requirements of communication networks to support ToD services. SLRs on information and reliability for ToD use cases from 5GAA WG1 [33] are used as the basis for this study. Inputs from research projects 5GCroCo, H2020 INGENOUS, and 5G-MOBIX are also discussed in this section to further understand requirements in various ToD scenarios.

6.6.1.1 ToD data rate and reliability requirements from 5GAA WG1 [33]

5GAA WG1 has released SLRs including the communication data rate and reliability for ToD use cases. The following subsections summaries the relevant requirement values for Tele-operated Driving, ToD Support, ToD for Automated Parking, Infrastructure-based ToD, and Automated Valet Parking use cases.

Table 8: Tele-operated Driving, ToD Support, and ToD for Automated Valet Parking (Direct Control ToD)

Information requested/generated	Quality of information / Information needs	**Uplink:** From Host Vehicle (HV) to ToD operator: 32 Mbps (video streaming) Or From HV to ToD operator: 36 Mbps (if video streaming and Object information is sent)	From HV to ToD operator: ~8Mbps are needed for a progressive high-definition video/camera (h.264 compression). Assuming four cameras are needed (one for each side): 4*8 = 32 Mbps. From HV to ToD operator (optional): Sensor data (interpreted objects) are also provided from the HV to the ToD operator. Assuming 1 kB/object/100 ms and 50 objects, the result is 4 Mbps.

		Downlink: From ToD operator to HV: Up to 1000 bytes per message (up to 400 Kbps) (Commands from ToD operator)	From ToD operator to HV: The type of command messages, e.g. a) turn steering wheel, direction, angle, etc., b) apply the brake, brake pressure, etc. including appropriate security headers. The command messages will be sent every 20 ms (maximum 50 messages per second).
Service level reliability	%	**Uplink:** From HV to ToD operator: 99	The video streams and/or sensor information should be sent with 'high reliability' to make sure that the ToD operator has the correct (current) view of the surroundings.
		Downlink: From ToD operator to HV: 99.999 (Very high)	From ToD operator to HV: The transmission of commands or paths from the ToD operator requires a very high level of reliability because this affects the safe and efficient operation of the AV.

Table 9: Tele-Operated Driving Support and ToD for Automated Parking (Indirect Control ToD for max. speed 20 km/h)

Information Requested/Generated	Quality of information / Information needs	**Uplink:** From HV to ToD operator: 32 Mbps (video streaming) Or From HV to ToD operator: Optional: 36 Mbps (if video streaming and object information is sent)	From HV to ToD operator: ~8 Mbps are needed for a progressive high-definition video/camera. Four cameras are needed (one for each side): 4*8 = 32 Mbps From HV to ToD operator (optional): Sensor data (interpreted objects) are also provided from the HV to the parking ToD operator. Assuming 1 kB/object/100 ms and 50 objects, the result is 4 Mbps.

		Downlink: From ToD operator to HV: Up to 25 Kbps (Path from ToD operator)	From ToD operator to HV: The data of provided paths are several Kbps (e.g. 100 points and 32 bytes for each point).
Service level reliability	%	**Uplink:** From HV to ToD operator: 99	The video streams and/or sensor information should be sent with 'high reliability' to make sure that the ToD operator has the correct (current) view of the surroundings.
		Downlink: From ToD operator to HV: 99.999 (Very high)	From ToD operator to HV: The transmission of commands or paths from the ToD operator requires a very high level of reliability because this affects the safe and efficient operation of the AV.

Table 10: Infrastructure-based Tele-operated Driving

Information Requested/Generated	Quality of information / Information needs	From RADAR to local compute unit for sensor fusion 80-160 Kbps From cameras to local compute unit 5-8 Mbps per camera (video streaming) From LIDAR sensors to local compute unit: 35 Mbps per sensor	Assumes RADAR sensors already generate object lists for observed vehicles, then the required bandwidth depends on traffic density. The number of cameras needed depends on the complexity of the road including number of lanes. Each camera is separately connected to the edge computer. This assumes also H264 compression. Video pre-processing, detection and classification of objects by camera is computationally intensive, therefore connecting more than two cameras to a state-of-the-art server is currently unlikely. Assuming each LiDAR sensor create point clouds and not object lists. This could happen on the same compute node. Therefore, this data rate requirement will be handled by local buses like Peripheral Component Interconnect Express (PCIe).

		From Infrastructure to ToD operator: Stream of environmental data after sensor fusion at the edge	Pre-processed environment model data e.g. in form of object lists that contain among others vehicle types, size, speed and direction requires only limited bandwidth, depending on the number of objects in the environment model this is estimated between 50-500 kbps.
		From ToD operator to HV: Up to 1000 bytes per message (up to 400 Kbps) (commands from ToD operator)	From ToD operator to HV: A machine-based ToD operator will most likely transmit trajectories instead of direct actuation commands. The type of command messages, e.g. a) turn steering wheel, direction, angle, etc., b) apply the brake, brake pressure, etc. including appropriate security headers. The command messages will be sent every 20 ms (maximum 50 messages per second).
Service level reliability	%	From sensors to edge compute node: 99	This is comparable to the sensor inside the car. The video streams and/or sensor information should be sent with 'high reliability' to make sure that the ToD operator has the correct (current) view of the surroundings.
		From ToD operator to HV: 99.999 (Very high)	From ToD operator to HV: The transmission of commands or paths from the ToD operator requires a very high level of reliability because this affects the safe and efficient operation of the AV.

Table 11: Automated Valet Parking (Infrastructure-based Direct Control ToD for max. speed 30 km/h) [23]

Information requested/ generated	Quality of information / Information needs	From HV to Automated Valet Parking System (AVPS): 0.2 Mbps (Cyclic status message from HV to AVPS)	From HV to AVPS: Cyclic message regarding the condition of the HV to the Remote Vehicle Operation Sub-system

		From AVPS to HV: Up to 0.2 Mbps (cyclic status message from AVPS to HV), up to 0.1 Mbps (non-cyclic messages, manoeuvre instructions sent from AVPS)	From AVPS to HV: The size of driving motion instructions towards the available parking spot sent from Remote Vehicle Operation Sub-system. The data are several KB – path or trajectory related data elements are transmitted.
Service level reliability		From HV to AVPS and From AVPS to HV: → 99.9% (Medium)	From AVPS to HV: Communication reliability only affects availability of the AVPS and not safety. The system is designed in a way that any disruption to the communication results in safe behaviour.

6.6.1.2 ToD data rate requirements from H2020 INGENIOUS project [34]

There are several flows of information with different requirements in terms of data rates and latencies. Figure 19 shows a reference classification of flows in the ToD system implemented in H2020 INGENIOUS for Automated Guided Vehicles (AGVs).

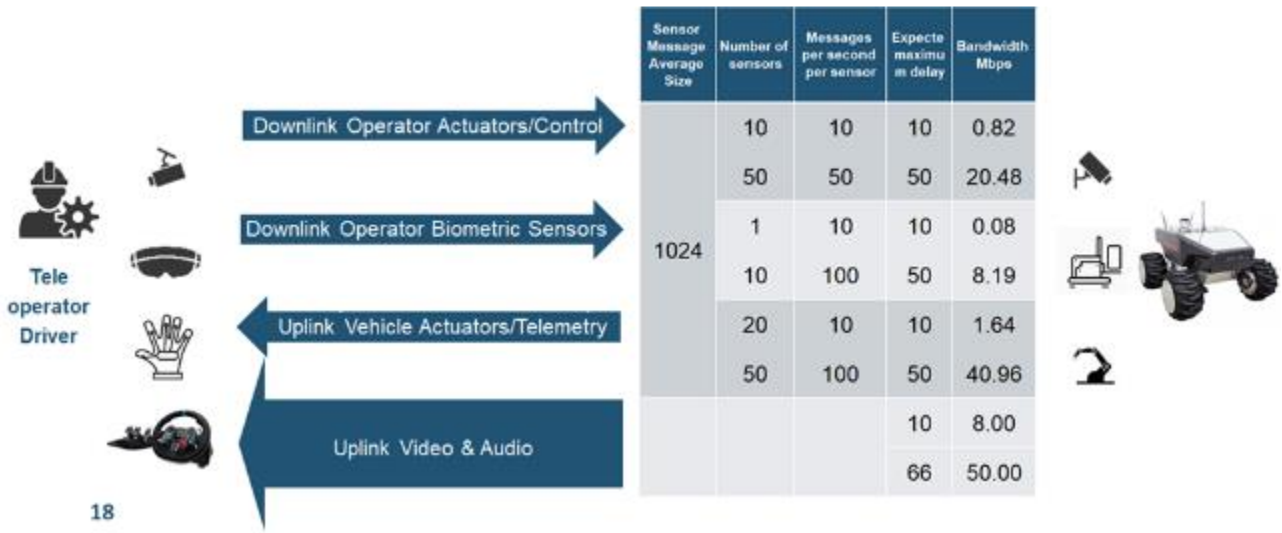


Figure 19: Information flows for ToD service [34]

This implementation of ToD service for AGVs contains the following information flows:

- Downlink ToD Operator Actuators/Control: this flow of information includes the vehicle remote actuators controls for speed, direction, lights, sound, etc
- Downlink ToD Operator Biometric Sensors: this flow of information includes biometric data to verify that the operator is in good shape to continue with the remote operation
- Uplink Vehicle Actuators/Telemetry: the information transported in this flow includes the GPS position, and all vehicle sensors information needed by the ToD operator like direction, acceleration, speed, radio signal, etc, as well as information about actuators in response to the ToD operator instructions.
- Uplink Video & Audio: this information flow contains latency-sensitive video and audio signals from the vehicle to the ToD operator.

More information flows may be required in other ToD use cases, but the aforementioned information flows are the main flows for most ToD use cases. Depending on the speed and dynamics of tele-operated vehicles, the maximum tolerated delay and the required bandwidth may be different. Therefore, Figure 19 shows the range of possible requirement values for different use case scenarios. These information flows can be transported using QoS flows in the cellular system matching the QoS characteristics, as defined by 5QIs for the 5G system. (See Annex B.)

6.6.1.3 ToD data rate and reliability requirements from 5GCroCo project

As introduced in Section 6.5.2.2, ToD user stories have been specified in the 5GCroCo project. The corresponding data rate and reliability requirements of user story 1 and 2 are summarised below [6] [38]:

Table 12: 5GCroCo ToD user story 1 – Remotely Controlled Manoeuvring (Direct Control ToD, low velocity < 15 km/h)

KPI Title	KPI Unit	KPI Value
Information exchanged and estimated payload	[bit/s]	Uplink: 10-50 Mbits Downlink: max. 500 Kbits
Service level reliability	[%]	Uplink: 99% Downlink: 99.9%

Table 13: 5GCroCo ToD user story 2 – Remotely Controlled Trajectory-based Driving (Indirect Control ToD, low velocity < 15 km/h)

KPI Title	KPI Unit	KPI Value
Information exchanged and estimated payload	[bit/s]	Uplink: 8-30 Mbits Downlink: max. 300 Kbits
Service level reliability	[%]	UL: 99% DL: 99.9 %

The 5GCoCo project also investigates remote driving scenarios with less demanding UL configurations, for situations of low QoS or to reduce uplink bandwidth requirements. [6] [38]

6.6.2 Minimal video quality for ToD operation by VQEG collaboration and data rate requirements from 5G-MOBIX [36]

For ToD the video must be encoded with low latency settings, which implies higher bit-rate and lower quality than with other conventional broadcast video coding settings. The quality of the low latency video is very relevant for safe driving by the ToD operators. So, there is a required minimal level of quality for the transmitted videos.

Three factors are relevant to the driving experience for a given camera: the speed of driving, the camera location, and the current manoeuvre in which the car is involved. The speed of driving affects the video quality because differences between one frame and the next increase with greater speed. As a result, the compression algorithms require more bandwidth to keep the same video quality. Camera location is also critical for video quality, as lateral cameras are less relevant to some types of driving tasks and experience more differences between frames compared with the front camera. Therefore, we need to consider the relevancy of the camera information and the quality that can be provided with a given bit-rate. Finally, vehicle manoeuvres may change the relevance of lateral or rear cameras, e.g. in parallel parking and reverse driving scenarios.

Figure 20: Video frames from four camera cars views

Each relevant combination of camera locations and driving speeds generates video streams with different scene characteristics. A set of representative streams, compressed at different bit-rates, should be evaluated to assess its perceptual difference with respect to the original ones, using a standardised methodology such as ITU-T P.913 [35]. The resulting evaluation would produce rate-distortion curves such as the ones in Figure 21.

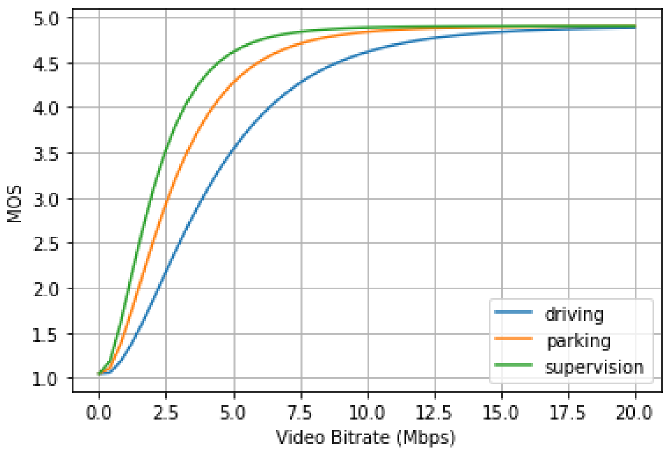


Figure 21: Example of estimated video bit-rate vs. Mean Opinion Score (MOS) for a frontal camera in several ToD scenarios

The Video Quality Experts Group (VQEG) [37], within its working group 5G-KPI, is currently designing a work plan to subjectively evaluate a relevant set of ToD video streams, so that such rate-distortion curves can be generated for a more diverse range of camera positions and driving conditions.

Note that the required level of visual quality for each camera (i.e. the required MOS) may also vary depending on per-use-case factors such as the specific manoeuvre to be performed or the distribution of displays on the ToD operator side.

6.6.3 Summary

Studies in 5GAA WG1 and different research projects show that communication data rate and reliability requirements of the ToD services vary for different service types, use cases, and scenarios. Many other factors also influence these requirements, e.g. vehicle speed, environment, sensor setting, video quality requirements. As discussed in section 6.6.1.3, a ToD service may need multiple information flows between the vehicle and the ToD operator, and each information flow may have specific performance requirements. It is not possible and there is also no need to identify data rate requirement values applicable to all ToD services.

Table 14 summarises the type of information and example range of data rate and reliability requirements for ToD services based on SLR values from 5GAA WG1 [33] and inputs from other research projects. It must be noted that the value ranges in Table 14 are understood as an indication of the magnitudes instead of strict requirement values, and types of information in the table are not comprehensive. A given ToD use case may only need part of the information in Table 14 and the exact requirement value may be different from the example range shown in the table.

Table 14: Type of information and example requirements of data rate and reliability of ToD services

Data type	Data rate	Note
Uplink (vehicle to ToD operator)		
Video (for human ToD operator)	Up to 32 Mbps	From HV to ToD operator: ~8Mbps are needed for a progressive high-definition video/camera (h.264 compression). Assuming four cameras are needed (one for each side): 4 * 8 = 32 Mbps. [5] Reliability: 99%
Object information	Up to 4 Mbps	Sensor data (interpreted objects) are also provided from the HV to the parking remote drive We can assume 1 kB / object / 100 ms. So, if we assume 50 objects per we end up with 4 Mbps. [5] Reliability: 99%
Audio	~96 Kbps	Audio signal provide acoustic environmental information to the ToD operator. Audio signal may be embedded in video stream. This signal can also be used for the ToD operator to have interactive audio communication with the passengers on-board.
Vehicle information (e.g. speed, acceleration, vehicle position)	~0.2 Mbps	50 km/h is considered the maximum speed for remote steering under highly uncertain conditions. In the ToD support case or in ToD for Automated Parking the maximum speed is 10 km/h and 20 km/h, respectively.
Downlink (ToD operator to vehicle)		
Vehicle manoeuvre commands (Direct Control ToD)	~ 400 Kbps	The sise of command messages, e.g. a) turn steering wheel, direction, angle, b) apply the brake, brake pressure, etc. including appropriate security headers. The command messages will be sent every 20 ms (maximum 50 messages per second) [5] Reliability: 99.9% or higher
Driving path or trajectory (Indirect Control ToD)	~ 25 Kbps	From ToD operator to HV: The data of provided paths are several Kbps (e.g. 100 points and 32 bytes for each point). [5] Reliability: 99.9% or higher
Keep alive signal	~ 0.2 Mbps	An example of this signal is the cyclic status message from Automated Valet Parking System to the vehicle for the AVP use case. [23] This signal is only needed when there is no periodic high frequency transmission of driving instruction commands from the ToD operator to vehicle, e.g. in Indirect Control ToD.

Control signals (e.g. for camera setting)	Negligible	This signal is not continuous data stream and of very low data rate.
Video/Audio (communication with ToD operator)	Video ~ 8 Mb/s Audio ~ 96 kb/s	These signals are applicable only when the human ToD operator needs interactive audio and/or video communication with the passengers in the vehicle.

The 5GAA SLR document and reports from research projects indicate more stringent reliability requirements for the downlink information, i.e. manoeuvre commands or instructions from the ToD operator to the vehicle, than uplink information, i.e. vehicle sensor data to the ToD operator. This is because vehicle manoeuvring relies on timely, accurate and trustworthy control information from the ToD operator, particularly for Direct Control ToD use cases. It is worth emphasising that the requirement on communication reliability is to ensure ToD service availability, instead of safety considerations. As studied in the STiCAD XWI [26], a ToD system should always be functionally safe, which means the vehicle and ToD operator should be able to bring the system to a safe state even if the connectivity between them is broken.

To provide ToD services with the desired availability, latency requirements, data rate and reliability studies in Sections 6.5 and 6.6 need to be considered simultaneously when mapping them to the QoS flow supported by the cellular networks, as discussed in Section 7.4.2.

7 Enabler technologies for ToD

This chapter studies the enabler technologies of each sub-system fulfilling the requirements discussed in Chapter 6.

7.1 Vehicle sub-system

7.1.1 Vehicle sensor technology

To provide ToD services, application readiness and features inside the vehicle have to demonstrate a maturity level fulfilling technical requirements realised for automated driving, according to SAE Levels 3, 4 and 5. In the following sub-chapters, the main vehicle capabilities and technologies are listed with no claim of completeness in regard to technologies introduced in the future to enhance safe remote driving for ToD use cases.

State-of-the-art vehicles can contain a variety of sensors for monitoring their surroundings in real time ([11], e.g. a subset of the following sensors in the next sub-chapters are available in the Mercedes-Benz S-Class model year 2020 with the standard driving assistance package), to be prepared for SAE Level 3 automated driving capabilities.

C-V2X sidelink enables vehicles to communicate with each other and everything around them, serving as a Non-Line Of Sight (NLOS) and without relying on a cellular network. C-V2X in Rel 14/15 enables vehicles to broadcast Basic Safety Message (BSM) and Cooperative Awareness Message (CAM) to other C-V2X-enabled vehicles. 5G V2X sidelink introduces reliable multicast capabilities that enable advanced safety use cases to complement the basic safety messages. Advance safety use cases include cooperative sharing of sensor information via messages such as Sensor Data Sharing Message (SDSM) and Collective Perception Message (CPM). Information received via BSM, CAM, SDSM and CPM, once made available to the ToD remote operator may improve situation awareness and driving safety, in a similar way as it benefits for the in-vehicle user or system.

Note that in addition to the advanced sensors for monitoring the vehicle surroundings mentioned in the following subsections, there are also more common sensors belonging to the control and active safety systems of the vehicle that can provide relevant data for Direct Control ToD. For that ToD type, actuators in the operator station can enhance the situational awareness, making the driver feel more like they are physically in the vehicle being directly controlled through ToD. Examples of such actuation include: accurate force feedback (e.g. when cornering or doing emergency evasive manoeuvres), vibrations in the steering wheel (e.g. when crossing road markings), vibrations in the brake pedal (e.g. when ABS is activated), vibrations in the seat (e.g. engine vibration, tyre issues, etc.), and motion simulation (e.g. to feel a loss of grip, understeer/oversteer, terrain changes such as hills, banking, curbing, bumps, camber, and both left/right and fore/aft weight transfer). The data needed for these operator station actuators is provided by common vehicle systems such as the drive-by-wire system, ABS system, ESP system, lane-keeping system, and possibly extra sensors such as accelerometers and gyroscopes that capture motion details. Since these sub-systems and sensors are common technology, they are not discussed further in this section.

7.1.1.1 HD digital maps

High Definition (HD) digital maps are used to ‘perceive’ the environment, not only regarding static objects but also for changes in real time [9]. They allow vehicles to see around curves, through fog and over large vehicles obstructing the sensors . As the level of automation increases, so does the need for HD digital maps. Higher quality and more detailed map content will be required, to support sensor data and guarantee driver safety and comfort.

The latest HD maps show a wealth of information, not just for roads and routes. The environment is captured completely in many billions of pixels and is accurate to the centimetre. All this data is captured and displayed in three-dimensional images. The raw material for the map may be provided by different sensors: LiDAR is one of the most common. A highly sensitive, vehicle-mounted laser scanner shoots high-frequency pulses of laser light. These are reflected by objects and returned to the sensor, which can measure the distance from each individual point. [10]

An HD map can be seen as an additional sensor in the vehicle. Data from other sensor technologies such as camera, RADAR and LiDAR are compared to it, providing the vehicle with all pre-recorded details about the environment, including information outside the sensors’ range.

HD digital maps and ToD

HD maps are an important enabler for ToD services, especially in scenarios such as Dispatch ToD, where the ToD operator takes on the role of Dispatcher, which is only to perform the strategic-level operations of driving, while the Tactical and Operational level operations are performed by the in-vehicle system [2]. If the in-vehicle system supports higher levels of automation, it will require centimetre-level accurate representation of the road, including attributes such as lane models, traffic signs, and other road infrastructure as well as lane geometry, in order to carry out its automated functions in a safe and comfortable manner.

This technology could also be used by the ToD provider to cross-check real data received by HD cameras in the vehicle with data from the generated HD maps, to detect deltas and work with extreme accuracy even in the worst weather conditions.

7.1.1.2 Precise positioning

Precise positioning refers to a series of techniques, which correct GNSS system errors to provide a higher level of position accuracy in the vehicles, with errors as small as a few centimetres under good conditions.

To assist and enable automated driving decisions, vehicles need at least lane-level precision (<30 cm) with very high integrity. If the level of automation increases, these requirements are even higher. This is something that cannot be achieved by typical GNSS systems, which provide a navigation accuracy of 3-5 m in clear conditions, but could be worse in bad weather conditions.

Other localisation requirements for vehicles with higher levels of automation are:

- High accuracy: Centimetre-level precision
- Integrity: High reliability with a guarantee for performance
- Availability: Fast convergence times measured in seconds, not minutes
- Scalability: Performance for millions of concurrent users

Precise positioning and ToD

Precise positioning is a key enabler for tele-operated services, especially in ToD Types 1 and 2, where the operational level actions (sustained lateral and longitudinal vehicle motion control) are performed by the in-vehicle systems with higher levels of automation. Thanks to precise positioning, the vehicle will stay in its lane. It also allows the vehicle to drive safely and accurately within the landscape of the local environment, acting as an additional sensor. This is of special importance in scenarios with bad weather conditions, such as heavy snow, where other sensors might not work properly.

7.1.1.3 LiDAR capabilities

LiDAR technology is used to monitor the environment actively and in combination with the HD digital maps to precisely adapt the environmental perception to the short-term changes in the environment. Detailed advantages and disadvantages of this technology are given in [12]. The main advantages are the ability to operate under difficult conditions (e.g. in darkness) between 50 m to 500 m, scan angles of up to 180 degrees, and its spatial imaging ability which identifies colours. Disadvantages include recognition or identification problems (i.e. objects can only be referenced according those already known or classified) and there are problems in foggy and rainy weather conditions. Other information on LiDAR can be found in [13], highlighting the technical details of available LiDAR products and automotive use cases such as traffic jam assistants and automated driving. The main applications in ToD would be for Dispatch ToD and Indirect Control ToD, where the driving operations are performed by the in-vehicle user/system.

7.1.1.4 RADAR capabilities

As with LiDAR, the well-known RADAR technology is also used to actively monitor the environment. However, here the distance of object detection is limited to around 250 m and there is also a reduced scanning angle. But on the plus side, RADAR systems are effective for short distances (starting at 0.2 m) and are able to detect all relevant environmental values (angle, distance, speed, material parameters) at once without further processing needs. Further advantages and disadvantages are given in [12].

The main applications in ToD would be for Dispatch ToD and Indirect Control ToD, where the driving operations are performed by the in-vehicle user/system. Also for Direct Control ToD , where the driving operations are performed and controlled directly by the ToD operator, the use of RADAR is viable as its operation area also covers the area nearby (>0.2 m) the vehicle.

7.1.1.5 Ultrasonic capabilities

Ultrasonic technology is a well-known and deployed technology, used to actively monitor the near field (<1 m) environment of the vehicles.

The main application in ToD would be for Direct Control ToD , where the driving operations are performed and controlled directly by the ToD operator. The consideration here would be to avoid collisions with nearby obstacles, e.g. for the ‘Tele-Operated Driving for Automated Parking’ [2] or in similar environmental use cases with a high density of obstacles for ToD to consider, such as busy container ports.

7.1.1.6 Video camera capabilities

Video cameras are used to support the vehicle’s LiDAR and RADAR measurements and can be used by a ToD operator of Direct Control ToD [2], to monitor the environment and also the passenger conditions. They can be installed on or in the vehicle (inside/outside) or on different infrastructures such as RSUs, lamp posts and traffic masts.

As listed in [12], the advantages are the operating range from 50 m to 500 m with up to 180-degree scanning angle, the ability to recognise colours as well as the possibility to generate spatial imaging and operate in the dark. The disadvantages of video cameras are most felt in foggy weather conditions or when the lens is soiled or images are subject to optical illusions.

7.1.1.7 Microphone and loudspeakers

Microphones and loudspeakers are well-known and deployed technologies used to monitor and actively interact with the environment, e.g. passenger to ToD operator conversations, detecting relevant outside communication and sounds (e.g. police instructions or emergency vehicle sirens). This is relevant mainly in the case of Direct Control ToD.

7.1.2 Vehicle actuator technology

From a functional ToD perspective, the main requirement is that the Host Vehicle should be equipped with drive-by-wire capabilities, i.e. steering, braking, acceleration and gearbox control, and that the interface to that drive-by-wire vehicle sub-system is open towards the ToD vehicle sub-system.

From a functional safety perspective, it is important that the HV’s advanced driver assistance system (ADAS) and drive-by-wire system is able to override the ToD vehicle sub-system and come to a safe standstill in the event that the ToD vehicle sub-system malfunctions [26], e.g. loss of connectivity or other fault leading to the creation of faulty actuation data, and that the vehicle can safely continue its path for a few seconds if there is a very short connectivity disruption, e.g. by combining adaptive cruise control and lane-keeping ADAS functions.

7.2 ToD operator sub-system

The ToD display system could include several monitors to present the remote video with low latency, but can also be implemented with 360-degree display devices in order to provide full, immersive experiences. These devices should introduce low latency in the video presentation in order to guarantee the most updated view of the remote environment (i.e. where the vehicle is heading).

In the following picture, we can see a real representation of a remote ToD operator with the immersive view from a virtual digital twin of the real vehicle. The video presented in the vehicle windows is from the low latency video signal captured by the cameras installed in the vehicle.

Figure 22. Nokia immersive cockpit from H2020 5GMOBIX.

New devices such as globes (360-degree dome-shaped sensor and haptic interface) or other biometric devices will be incorporated in the ToD cockpits, such as the one implemented in the H2020 INGENIOUS project presented in Figure 23. In this project, remote AGVs can be controlled with globes that can work with hand gestures. The globes also support actuators that transmit electrical signals to the operator's skin in order to provide an additional information channel. Other human biometric sensors like belts can provide real-time information about the ToD operator.

Figure 23. Nokia immersive cockpit from H2020 INGENIOUS

7.3 Infrastructure sub-system

As with other forms of ToD, the infrastructure supported case requires fast and reliable wireless network connectivity between operator and vehicle. In addition, network communication is also required between sensors and a local compute node or edge node. Depending on the local conditions these connections can be implemented in wired or wireless versions. For more details on wireless connectivity we refer to Section 7.4.

7.3.1 Sensors

The same sensor types as found in automated vehicles can be applied in the infrastructure. These are video cameras, RADAR and LiDAR. Already in the vehicle some sensor types (e.g. RADAR) are used with different field-of-view and range options. Sensors deployed in the infrastructure will require an even wider set of configuration options with respect to range, field of view and resolution. Cameras of different focal length will be used to cover close, medium and far distances from where they are mounted. LiDAR sensors will require a higher vertical resolution because they are usually mounted higher than 4 meters above the height of trucks to avoid occlusion. At the same time, they will be tilted downward in contrast to LiDAR mounted in vehicles closer to ground level. There is a difference between indoor and outdoor scenarios; lower speed can be expected indoors but on the other hand there is a higher chance of occlusion due to pillars, walls and other parked vehicles. Therefore, indoor scenarios require a higher sensor density but with shorter range to achieve full coverage.

7.3.2 Edge-computing platforms

The infrastructure will apply sensor processing, machine-learning and communication algorithms to produce a 3D environment model out of sensor data, and communicate it to a human operator. In the case of a machine operator planning algorithms for route, manoeuvres and trajectory will be applied as well as a network protocol to communicate between infrastructure and vehicle.

7.3.2.1 Edge hardware

Edge hardware will require high-performance hardware for multi-modal fusion. It is conceivable that a multi-level architecture will emerge where the furthest edge layer will process data from a single sensor or a small number of the same sensor types (e.g. cameras). The next level of edge hardware can then perform multi-modal fusion to establish a complete environment model combining all sensors at its location. Specific accelerator hardware, such as a Graphics Processing Unit (GPU), Vision Processing Unit (VPU) or Field-Programmable Gate Array (FPGA), will be used to support the computational and machine-learning requirements. For instance, in Convolutional Neural Networks (CNN) for object classification in image data, the main operation is to Multiply and Accumulate (MAC), which needs dedicated hardware developed by different vendors.

7.3.2.2 Safe perception

The dependability of machine-learning models for environment perception is still under research. In the ideal case these models can perform in the 90% and above range for accuracy e.g. for object detection and classification. Since the performance of these models is highly dependent on input data it has been shown that the accuracy can suffer significantly from either data types that were not included in the training data, so-called Out of Distribution (OOD) data, or from ‘adversarial attacks’ which affect input data, e.g. images modified to cause misinterpretation of the input data by machine-learning algorithms. This topic is covered in both ISO 26262 and ISO 21448 Safety of Intended Functionality (SOTIF). ISO 26262 deals with hardware and software faults in the underlying system, SOTIF covers the data-related aspects of system (mis)behaviour. So, using ISO 26262 the faults that remain after safety design and mechanism phases take place can be estimated for the sensors themselves, and the hardware that the machine-learning models runs on. Modern machine-learning models have an inherent robustness meaning that only a certain percentage of hardware faults actually lead to safety critical faults on the level of these models. This is captured with the term Program Vulnerability Factor (PVF) which together with the Architectural Vulnerability Factor (AVF) and Timing Vulnerability Factor (TVF) determines how much of the nominal silent error rate leads to safety critical faults on the application level. Sensor, algorithm and actuator limitations are covered in SOTIF, which introduces the notion of known unsafe, known safe, unknown unsafe, and unknown safe scenarios. The ultimate goal is to evaluate both known and unknown unsafe scenarios and provide an argument that these areas are sufficiently small and, therefore, the residual risk is sufficiently small [2].

7.3.3 Automated driving stack for infrastructure

For a machine-only operator mere perception functionality is not enough. In fact, the functionality of an automated vehicle is to be transferred to the infrastructure. In both cases perception provides the first layer of environment detection related to static and mobile objects, road surface, free space, traffic signs, etc. This information is then combined to a complete environment model. The map and environment model are then used to plan trajectories and finally control the vehicle’s actuators. The main differences are that in the case of the automated vehicle the sensors are fixed on the car and show the vehicle’s ‘ego perspective’, whereas the infrastructure sensors are fixed and watch the vehicle from the outside. Furthermore, in the infrastructure case, the actuation commands have to be transmitted over a wireless channel.

7.3.4 Environment simulation techniques

As described in Section 7.2, a virtual environment view is required when only infrastructure sensors are available. Precise, timely and realistic video representations of the environment are necessary for a human operator. When using only infrastructure sensors, no video data from the driver’s perspective is available, so needs to be reconstructed from the environment model. This environment model from the driver’s perspective can be constructed using environment simulation techniques.

7.4 Communication networks

ToD has already been implemented using 4G LTE networks in field tests [29], which acknowledged the role of communication in fulfilling the latency and data rate requirements of ToD services. 5G networks being deployed worldwide can bring a ten-fold increase in data rates compared with 4G networks and extremely low latency (under 10 ms) combined with high reliability. With increasing market penetration of ToD services, especially in ToD Stage 2 and 3, it is foreseen that continuously improving 5G networks will play a major role in ToD communication solutions, especially when the system capacity demand becomes challenging for the existing 4G networks. As studied in [31], ToD service is a major advanced V2X use cases driving V2N spectrum demand, and which needs to be considered by spectrum regulators in facilitating connected and automated mobility applications.

The following subsections discuss additional key technologies and features of cellular networks enabling market deployment of ToD services in different operational and market environments.

7.4.1 Cross-MNO performance improvements

7.4.1.1 Solutions to improve cross-MNO network reselection performance

Continuity of communication between the vehicle and ToD operator is important for ToD services. When a vehicle moves across the country border and the on-board UE leaves its serving mobile network, an interruption in communication occurs. Connecting to a new mobile network can take up to several minutes, e.g. scanning the spectrum to find a Public Land Mobile Network (PLMN) it can use, if no special measure is taken to improve the network reselection process.

To mitigate such a problem, from the UE side, the modem can retain necessary information to assist network reselection or optimise the PLMN scanning algorithm for the carrier frequency of allowed PLMNs. Information provided on the SIM card, e.g. the information of roaming partners, can also speed up the network reselection process. New UE registrations to visited PLMNs can interrupt service because the user plane needs to re-establish a connection with the Packet Data Gateway (PGW) of its home PLMN. To maintain service continuity, the ideal solution would be to orchestrate a seamless handover from the network side.

The 5GAA Network Reselection Improvements (NRI) XWI [20] has proposed technical solutions based on 3GPP specifications to significantly improve the cross-MNO performance in 4G and 5G networks while maintaining the continuity of IP connectivity.

- In the first solution, namely UE roaming with Mobility Management Entity (MME in 4G) / Access & Mobility Management Function (AMF in 5G) relocation, the standardised interface S10 (N14 in 5G) between MMEs (AMFs in 5G) from different PLMNs is implemented to prepare and assist the UE in the process of roaming to the Visited-PLMN. Figure 24 and Figure 25 illustrate the architecture of the proposed solutions in 4G and 5G networks, respectively. As a result, the interruption time can be brought from several minutes down to about 1 second. [20]

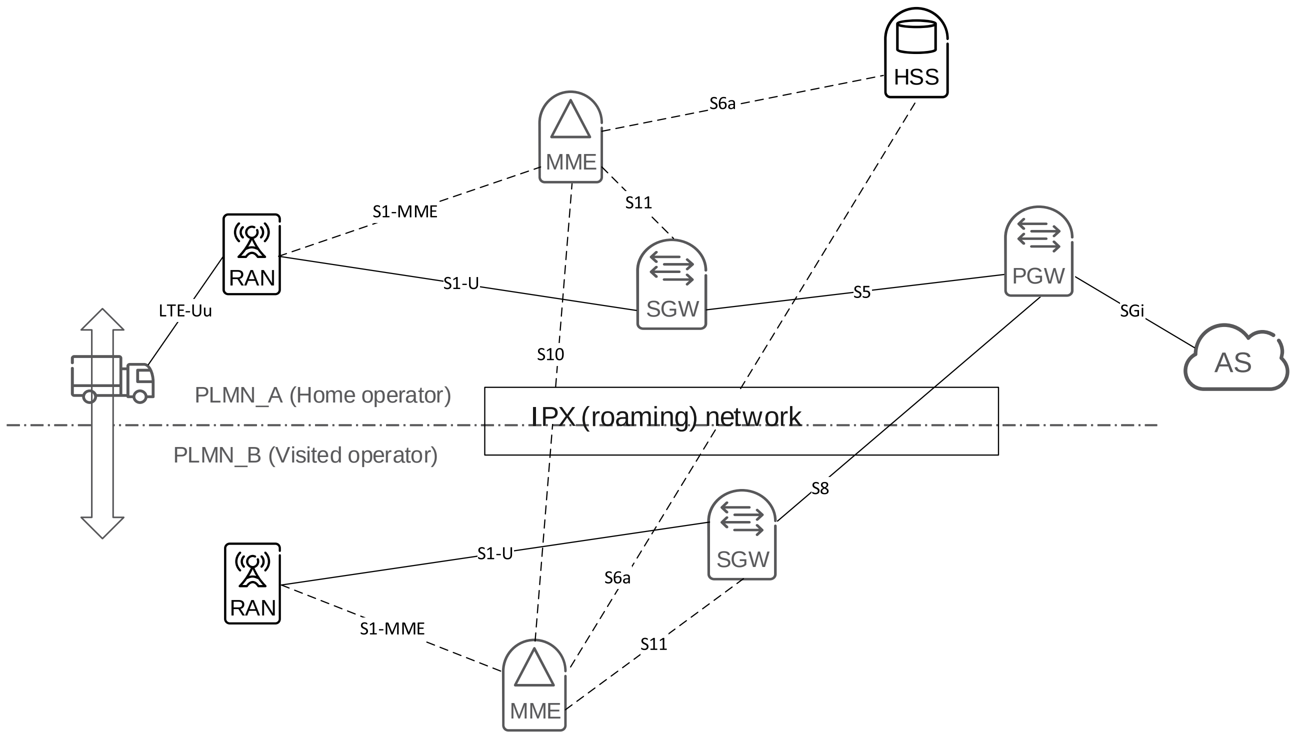


Figure 24: 4G roaming architecture with S10 interface [20]

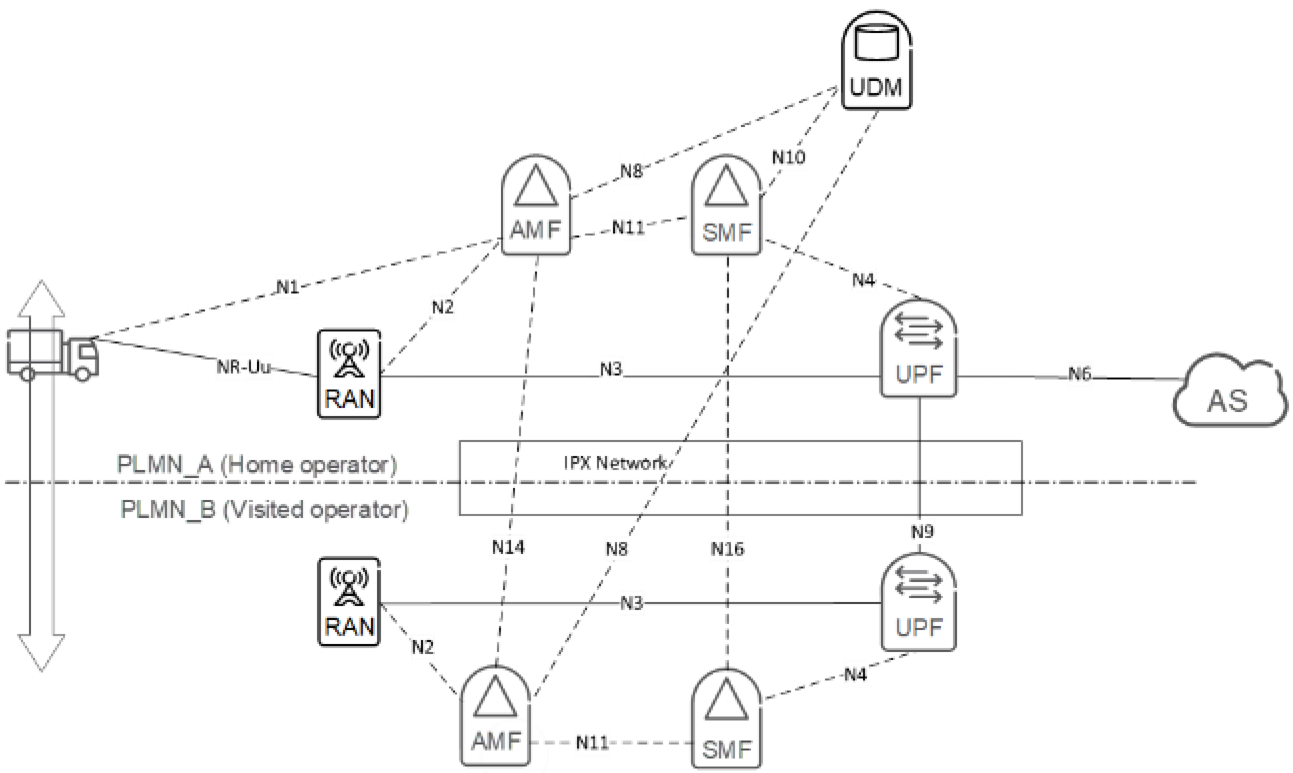


Figure 25: 5G roaming architecture with N14 interface

- To further improve the performance, a handover between PLMNs, as already defined in 3GPP, can be implemented with the S10 (N14 in 5G) interface between MMEs (AMFs in 5G) of different networks. In this case, additional static and dynamic information, e.g. neighbouring cell lists, interconnecting traffic and signalling links, as well as real-time signalling information related to target cell selection, etc. need to be available between the relevant MNOs. [21] This solution can further reduce the interruption to ~0.1 second. [20]

Field tests have proven the effectiveness of the proposed solutions in improving cross-OEM performance. [21] However, there are still subjects to be studied from the operational and business perspective, to commercially deploy these solutions. For example, to implement the cross-PLMN handover solution, special roaming agreements including sharing sensitive information regarding radio network configuration need to be agreed among MNOs. [20]

7.4.1.2 Cross-MNO network reselection improvement and ToD

In ToD Stage 1, services are provided to automated vehicles in confined areas, e.g. car OEM factory, ports, airports, etc. In ToD Stage 2, vehicles operate in predetermined areas or following predefined routes on public roads. It is possible for an MNO to build network coverage for such areas, especially when the fleet owner or ToD Service Provider prefers signing up with one MNO. In such cases, the system can operate within the coverage area of the same network, i.e. without crossing-MNO issues. In ToD Stage 2, when the ToD service area is covered by networks from multiple MNOs, and in ToD Stage 3, where automated vehicles can move over a longer distance and across country borders, crossing-MNO network reselection improvement becomes relevant for ToD operations across MNO network borders.

The impacts of network reselection performance should be evaluated for use cases considering specific operational scenarios and performance requirements, e.g. whether the change of serving PLMN/MNO occurs during use case execution and what potential implications this may have on connectivity (i.e. interruptions). Additionally, supplying network coverage maps to the vehicle can help the application adapt its behaviour in advance to mitigate the impacts of connectivity interruption. As discussed in sub-section 7.2.2.3, predictive information about network QoS, once available from the network, may support further adaptive behaviour of the applications, as currently studied in 5GAA PRESA XWI [39].

ToD service is needed only when the automated vehicle encounters a situation that the automated driving system cannot handle. In such a case, the tele-operated vehicle usually moves at a low speed and the latency requirement is relatively loose. Cross-MNO network reselection performance becomes relevant for ToD operations only when the vehicle requests ToD service at the border of MNO networks, which is a rare event. Considering the stringent latency requirement of Direct Control ToD, as discussed in Section 6.5, the suggested course of action is to avoid Direct Control ToD operation when vehicle move cross country borders. In this case, the network coverage map and predictive QoS information about the network can help the ToD operator and vehicle to disengage Direct Control ToD, or switch to alternative solutions before crossing a border, e.g. Indirect Control ToD. Nevertheless, good coverage along the road network and improved network reselection performance at network borders are important for the availability of ToD services assisting, complementing, and boosting automated driving on public roads. Mobile network QoS can be used by the applications to ensure that enough capacity is available in case it becomes necessary to activate ToD services.

7.4.2 QoS provisioning and predictive QoS

Mobile networks support Quality of Service differentiation for packet-switched services. QoS technologies ensure the operation of high priority applications with limited network resourced by providing differentiated handling and capacity allocation to specific flows in the network. QoS can be activated by identifying traffic flows or through applications interacting with the mobile network.

7.4.2.1 QoS framework of 5G network

In the 5G System, QoS Flow is the finest granularity for QoS differentiation. QoS Flow is identified by a QoS Flow ID (QFI). A PDU Session, which provides the end-to-end user plane connectivity between the UE and a Data network, can support one or more QoS Flows. All traffic mapped to the same 5G QoS Flow receive the same packet-forwarding treatment e.g. scheduling policy, queue management policy, rate-shaping policy, Radio Link Control (RLC) configuration, etc. Figure 26 shows the 5G QoS framework, as described in 3GPP TS 23.501 [14]. Both QoS Flows that require guaranteed flow bit rate, i.e. GBR QoS Flows, and QoS Flows that do not require guaranteed flow bit rate, i.e. Non-GBR QoS Flows, are supported in the 5G System.

A QoS Flow may either be ‘GBR’ or ‘Non-GBR’ depending on its QoS Profile. According to 3GPP TS 23.501 [14], for each QoS Flow the QoS profile should include as QoS parameters a 5G QoS Identifier (5QI) and an Allocation and Retention Priority (ARP). For each Non-GBR QoS Flow, the QoS profile may also include Reflective QoS Attribute (RQA) as the QoS parameter. For each GBR QoS Flow, the QoS profile should also include the QoS parameters Guaranteed Flow Bit Rate (GFBR) for UL and DL; and the Maximum Flow Bit Rate (MFBR) for UL and DL. In the GBR QoS Flow case only, the QoS parameters may also include Notification control and Maximum Packet Loss Rate for UL and DL.

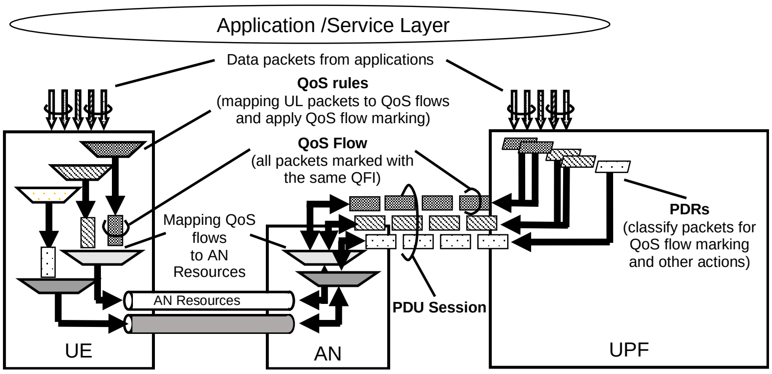


Figure 26: QoS framework in 5G [14]

The 5G QoS Identifier (5QI) is a scalar used as a reference to 5G QoS characteristics controlling QoS forwarding behaviour for the QoS Flow, e.g. scheduling weights, admission thresholds, queue management thresholds, link layer protocol configuration, etc. This may be implemented in the access network by the 5QI referencing node specific parameters that control the QoS forwarding treatment for the QoS Flow.

The 5G QoS characteristics associated with 5QI include: [14]

- Resource type (GBR, delay critical GBR or Non-GBR)
- Priority level
- Packet Delay Budget (PDB)
- Packet Error Rate
- Averaging window (for GBR and Delay-critical GBR resource type only) representing the duration over which the GFBR and MFBR should be calculated, e.g. in the (R)AN, UPF, UE
- Maximum Data Burst Volume (for Delay-critical GBR resource type only) denoting the largest amount of data that the 5G-Access Network (5G-AN) is required to serve within a period of 5G-AN PDB

Table 16 in Annex B maps the standardised 5QI values to 5G QoS characteristics.

Depending on the actual communication performance requirement of ToD services, corresponding 5QIs can be selected for the QoS Flows to enable the ToD session.

7.4.2.2 Predictive QoS

5GAA has previously investigated the relationship between application behaviour and achievable/verifiable network performance [16]. While a vehicle is moving, the network performance experienced over time and space varies (due to changes in, for example, network load, radio link quality), so automotive application designers must consider how to adapt application behaviour – for example, encoding, flow priority, packet inter-arrival time – to the changes in network performance. One example of such ‘application adaptation’ for a ToD session with a ToD operator, is video streaming from the vehicle to the ToD operator with variable resolutions to accommodate bit-rate variations. When the network enforces specific QoS treatments (e.g. a GBR flow with GFBR/MFBR), it tries to fulfil minimum requirements for the video to run without interruption and the application then manages adaptations between the minimum and maximum bit-rates. From this point of view, changes in video resolution could result in vehicle behaviour changes, e.g. speed reduction, because the video quality might not be enough to safely keep the current speed. Of course, the vehicle’s reaction will take a certain amount of time to be fully and safely completed. 5GAA, therefore, highlighted that adaptation capabilities for automotive applications should be designed with consideration of their impacts on vehicle behaviour, especially the interaction and time lag between the application adaptation and the corresponding change of vehicle behaviour [16]. Thus, while an application can adapt to the known boundaries, e.g. when the bit-rate is between the GFBR/MFBR, further support would be beneficial from the application side when changes are unknown to the application, e.g. when the bit-rate goes below the GFBR.

Motivated by the above investigation, 5GAA has developed the concept of Predictive Quality of Service [15][17], which is a mechanism enabling mobile networks to provide advance notifications about predicted QoS changes to interested consumers. This makes it possible to adjust application behaviour before the predicted QoS change takes effect, which is important to certain automotive use cases, such as ToD and automated driving. [16]

Three logical steps are needed for supporting Predictive QoS from the network perspective: [16]

- Step 1: Collecting Data – QoS prediction is assisted by data collection from different sources, such as vehicles, networks, and third parties (e.g. weather information).
- Step 2: Making Predictions – The computation is performed by the Prediction Function (PF) to produce content to be placed inside the QoS prediction notification (i.e. In-advance QoS Notification) [15], and using collected prediction supporting data.
- Step 3: Delivering Predictions – These procedures are required in order for the notification producer to deliver the QoS prediction to the intended consumers over the specified interfaces.

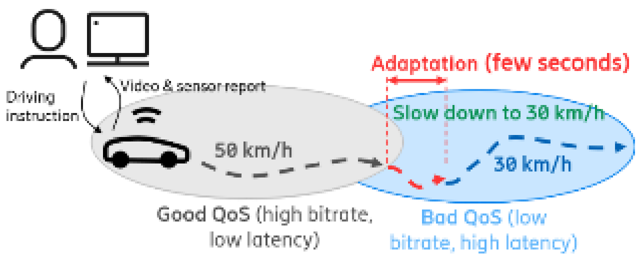
5GAA Technical Reports [15][17] provide detailed descriptions of the concept of Predictive QoS from multiple perspectives including system architecture, prediction function, location and algorithms, and delivery of notification.

7.4.2.3 Predictive QoS and ToD

For automotive use cases, the achievable QoS influences the settings of the driving behaviour, e.g. level of automation, trajectory, speed, inter-vehicle distance. This is very important for ToD use cases where remotely controlling a vehicle travelling at a high speed might require lower latency than remotely controlling a vehicle at a lower speed.

The reaction-based approach, i.e. reacting when or after a QoS change has happened, may be unsuitable for automotive use cases as the adaptation of an application may involve mechanical actions, e.g. slowing down a vehicle from 100 km/h to 70 km/h, which require a certain amount of time to be completed. In this case, the simple reaction of an application to network changes, e.g. slowing down a vehicle in the event of an unfulfilled QoS (due to radio congestion or changed channel quality) may result in instability for involved vehicles, as a vehicle being remotely driven at speed may not be tolerated by the current achievable QoS. Figures about human reaction time and mechanical reaction time can be found in [18]. Given the intrinsic mobility of vehicles, variation of coverage in different geographical areas as well as load variation across the cells visited by the vehicles might involve a range of network capabilities while a vehicle is moving. Solutions are needed to solve the challenge of how to handle the adaptation of V2X application behaviour to network changes. ToD is in the category of use cases where the application can adapt its behaviour thanks to QoS prediction.

As stated above, the adaptation of automotive applications usually requires mechanical actions, thus introducing a certain latency from the moment the application starts to react to the moment the reaction is completed. In addition to mechanical actions, one should also consider that the process of selecting a certain reaction is also influenced by other factors, i.e. a reaction might reflect more than just vehicle status/behaviour such as speed, which can further delay response time as it gathers and processes additional information). Other aspects that could influence the reaction selection process could be, for example, where the vehicle is being driven (urban, suburban, rural, etc.) and corresponding characteristics (e.g. presence of an emergency lane or of other lanes, or vehicle being close to a junction/intersection), information about other vehicles/road users in proximity, etc. This opens the following scenario: a network capable of predicting its QoS performance (e.g. changes of achievable QoS characteristics, usually referred to as QoS prediction) is able to quickly inform a V2X application about an expected change of achievable QoS, giving the application time to react to the expected change before the change takes effect. In the ToD case, an operator remotely driving a vehicle could be informed that, for example, in 30 seconds an increase of latency is expected, thus giving the application time to safely slow the vehicle down or adjust to the predicted situation. The ToD scenario is depicted in Figure 27. Given the achievable QoS in the two areas, in the ‘good QoS’ area the remote driver can safely control the vehicle up to a speed of 50 km/h, while in the ‘bad QoS’ area, the supported speed is up to 30 km/h. The bottom figure shows that, by using mechanisms related to QoS prediction that are able to provide timely notifications about an upcoming QoS degradation, the ToD operator is able to slow the vehicle in advance so it can be driven at a safe speed in the ‘bad QoS’ area.



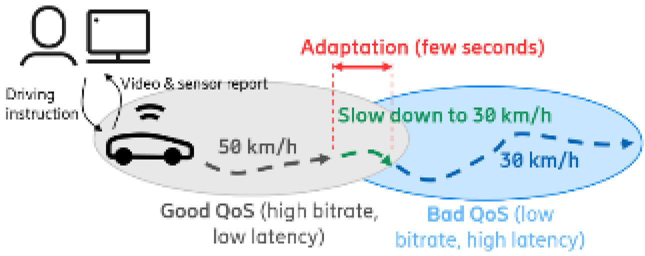


Figure 27: Example of application adaptation considering a change of QoS capabilities while a vehicle is moving that requires a reduction of speed in networks without QoS prediction (top) and with QoS prediction (bottom)

Predictive QoS will be an effective tool for ToD applications to adapt behaviours, e.g. vehicle speed or type of ToD, to the upcoming network QoS changes. Though predictive QoS can improve service availability and ToD user experience, it is not a mandatory feature for enabling ToD services from the functional safety perspective. The current LTE network with conventional QoS framework can already support ToD services in many scenarios. Applying predictive QoS to ToD services in deployment still requires further research and standardisation work, as being addressed in the 5GAA PRESA XWI.

7.4.3 Network slicing

A network slice is a logical network that provides specific network capabilities and characteristics in order to serve a defined business purpose or customer. Network slicing allows multiple virtual networks to be created on top of a common shared physical infrastructure. A network slice consists of different subnets, example: Radio Access Network (RAN) subnet, Core Network (CN) subnet, Transport Network subnet.

The fundamental 5G System Architecture and associated key technology components are maturing to enable network slicing. [30] [32] Customised network slices for guaranteed service level agreements can support independent business operations covering ToD services with different performance, functional and operational requirements.

7.4.4 Functional safety and service availability

The 5GAA study on functional safety [26] suggests that the system of Direct Control ToD needs to be designed according to Automotive Safety Integrity Level (ASIL) D. For Indirect Control ToD, lower ASILs should be acceptable, which depend on the capability of the vehicle to perform plausibility checks of the received Indirect Control commands through independent ego sensors in the vehicle and on the freedom the vehicle retains to decide its detailed trajectory. The study also concludes that it is possible to fulfil the safety requirements by applying the ‘black-channel’ approach in ToD systems using mobile communications. Instead of designing all components of the communication network with a safety integrity level according to relevant safety standards, the black-channel approach relies on the mechanisms to monitor the communication channel on both ends in a functional safe way and additional diagnostics or application functions at the connected elements to reach the desired safety integrity level. [26]

Although from the functional safety perspective cellular network features do not need to be designed strictly according to safety standards thanks to the black-channel approach, the high availability requirement of ToD services still require cellular networks to provide assurances for small outage ratios and high compliance with performance requirements. That is where QoS mechanisms of LTE and 5G networks play important roles. Additionally, Predictive QoS, when combined with proactive and adaptive ToD applications, can further improve the general availability and user experience of the ToD services.

ToD service availability also depends on the coverage of the mobile networks and the handover performance, as studied in Section 7.4.1, when a tele-operated vehicle crosses different mobile network borders. For market deployment of ToD services, especially in ToD Stage 2 and Stage 3 for cross-region mobility, it needs to ensure proper cellular network coverage on the relevant road networks and improved network reselection performance, as suggested in [27] and [20], respectively.

7.4.5 Communication security

Major security requirements of communications supporting ToD services include:

- End-to-end information integrity and confidentiality for data communication among components of the ToD system, especially between ToD Vehicle App and ToD Operator App from the Service Provider.
- Authentication of the communicating entities cross different stakeholder domains.

The state-of-the-art E2E security solutions can be applied to ensure communication security for ToD services, such as transport layer security TLS [28] using certificates from Public Key Infrastructure commonly used for session-based communication applications on the Internet.

8 Communication architecture

The different ToD use cases and specific requirements that they have, as presented in Table 1, pose different communication requirements for the realisation of the various ToD use cases and scenarios. This section presents the key components of the communication architecture involved in the realisation of ToD use cases and the required interfaces between the communication architecture and ToD sub-systems. The analysis has been split into three subsections, focusing on key features of different scenarios:

- Tele-operated Driving in Single-MNO Scenarios (Section 8.1) show the interfaces and mapping of ToD entities/system and 5G communication system, considering scenarios of Direct Control ToD and Indirect Control ToD etc. where a single MNO is needed, e.g. in a confined area of operation. This case is applicable for all stages of the ToD services roadmap defined in Section 4.2.

- Tele-operated Driving in Multi-MNO Scenarios (Section 8.2) show the roaming architecture and interfaces with ToD entities/system, considering use cases with more than one MNO is involved e.g. unconfined area of operation (open roads), cross-border scenarios. This becomes more applicable from the Stage 2 and beyond of the ToD services roadmap defined in Section 4.2.

- Infrastructure-based Tele-operated Driving Scenarios (Section 8.3) show the interfaces of infrastructure-based ToD with the communication architecture needed for all stages in the ToD services roadmap defined in Section 4.2.

It should be noted that the following sections present existing interfaces and functionalities that have been specified or standardised, without trying to define new functionalities and/or interfaces. Both 4G and 5G communication are taken into consideration.

8.1 Tele-operated Driving in Single-MNO Scenarios

Figure 28 depicts the 5G System (5GS) architecture in the non-roaming case, i.e. single MNO or Public Land Mobile Network (PLMN). A 5GS consists of the Next-Generation Radio Access Network (NG-RAN) and the 5G Core network (5GC) domains. The 5GC consists of several Network Functions (NF) such as the Access and Mobility Management Function (AMF), Policy Control Function (PCF), Network Data Analytics Function (NWDAF), Network Repository Function (NRF), Network Exposure Function (NEF), Unified Data Repository (UDR), Unified Data Management (UDM), Session Management Function (SMF) for establishment, modification or release of a session and User Plane Functions (UPFs), among others. It should be noted that in Figure 28 the NFs within the 5GC Control Plane (that includes all NFs except UPF) use service-based interfaces for their interactions, e.g. NPCF, NSMF, NNEF, NWDAF, etc. In service-based representation, NFs within the Control Plane enable other authorised network functions to access their services. In this specific case, the ToD Application Server is hosted in a cloud server (i.e. public domain network) so it is out of the MNO domain.

Figure 28 also shows the interfaces of the ToD Application Server and the ToD Vehicle with the 5GS, including both user plane and control plane interfaces:

- Interfaces between the ToD Application Server and the communication network:
  - N33/NFnef: Reference point between NEF and an Application Function (AF). This interface allows the ToD application server to request and receive information e.g. analytics, QoS prediction that the network provides. The NEF provides access to various services of the network. For instance, Nnef_AnalyticsExposure provides support for exposure of network analytics, Nnef_AFsessionWithQoS requests the network to provide a specific QoS for an AS session, etc.
  - N6: Interface between the UPF and a public data network for traffic forwarding.

- Interfaces between the ToD Vehicle and the communication network:
  - Uu: Radio interface between the vehicle and the radio access network to support both user plane traffic (e.g. ToD packets) and control plane traffic (i.e. network signalling packets).
  - N1: Reference point between the UE and the AMF for control plane signalling between the vehicle (user equipment/communication component) and the 5GS e.g. for measurements reporting, session management, etc.
- Interfaces between the ToD Vehicle application and the ToD Application Server:
  - $P1_{\_ToD\_Veh}$: Application layer interface used for secure connection between trusted ToD AS and ToD Vehicle Apps to exchange application layer information. This interface may use standard or proprietary protocols by ToD technology providers. This interface is usually implemented using cellular mobile communications (e.g. Uu interface for the radio interface, N3 for core network part and N6 from the core network to the public domain network).

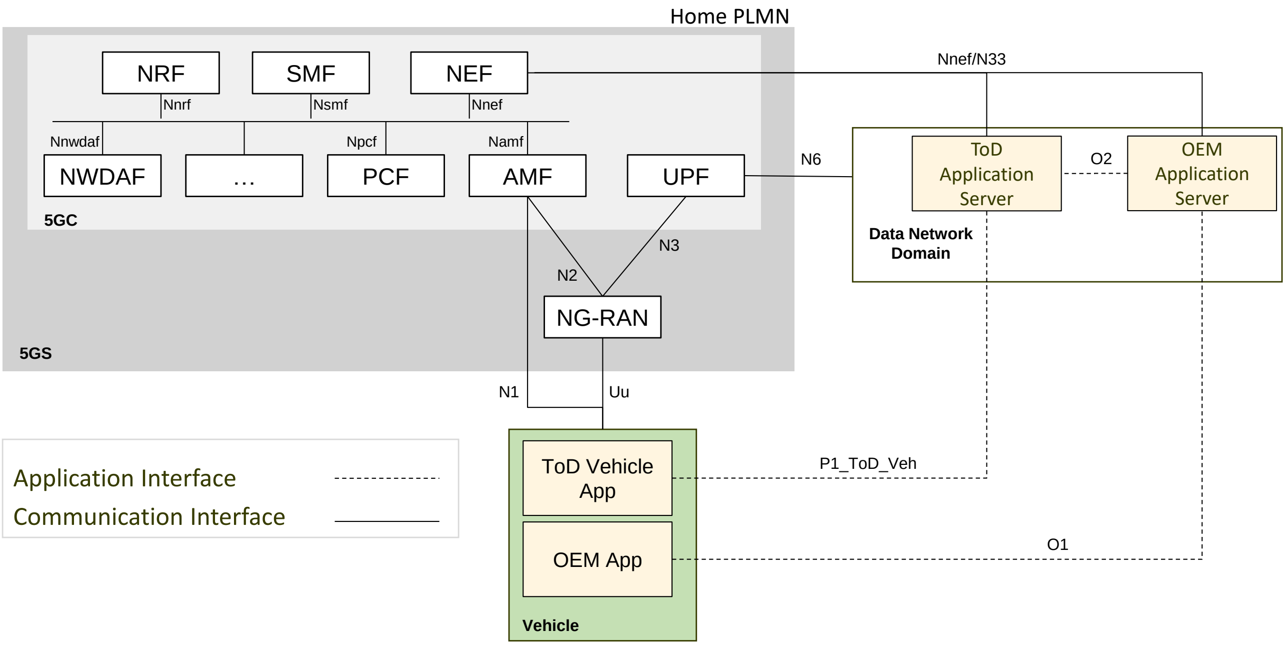


Figure 28 5G System Architecture (non-roaming case)

When an LTE communication network is used, the ToD Application Server uses the SGi interface to send data traffic to (or receive from) the communication network, while the T8 interface is used by the ToD Application Server to interact with the Service Capability Exposure Function (SCEF) of the communication network. The user plane traffic and the control plane traffic of the ToD vehicle use the Uu interface.

8.2 Tele-operated Driving in Multi-MNO Scenarios

In many scenarios the vehicle changes MNOs and receives connectivity services by different MNOs e.g. in cross-border scenarios. Figure 29 illustrates the roaming architecture with local breakout. The Home Public Land Mobile Network (HPLMN) refers to the network that a user subscribes to, while visited PLMN (VPLMN) is the network to which the UE roams to when leaving the HPLMN. When a UE roams, services provided by the HPLMN are used to provide ToD service-related parameters to the VPLMN. The local breakout is a deployment option where the Session Management Function (SMF) for establishing, modifying or releasing a session and all User Plane Functions (UPFs) involved in a Protocol Data Unit (PDU) session (i.e. a logical connection between the UE and network) are under the control of the VPLMN. Local breakout is critical to reduce the latency. The interfaces of the ToD Application Server and the ToD Vehicle with the 5GS are the same as those presented in Section 8.1.

Alternatively, home-routed roaming architecture could be considered, where the traffic is forwarded via the home UPF, while the SMF is under the control of the HPLMN. For HPLMN and VPLMN use, similar LTE communication networks options to those above apply.

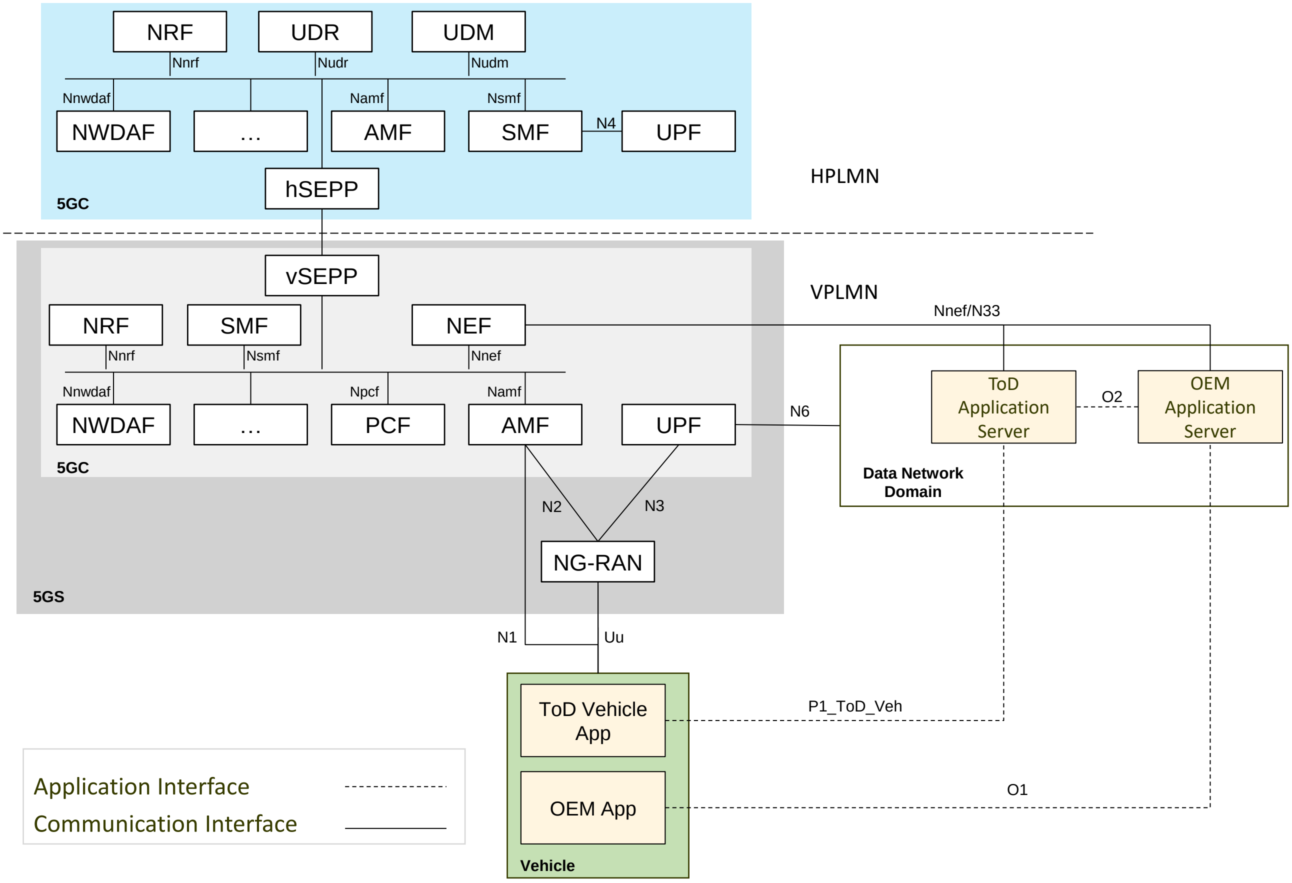


Figure 29: 5G System Architecture (roaming case, local breakout)

8.3 Infrastructure-based Tele-operated Driving Scenarios

In some scenarios, infrastructure could be used to support a ToD service. The term infrastructure in this section considers both road infrastructure and/or SP infrastructure. The infrastructure, according to the analysis in Section 5, consists of two parts: a) the infrastructure device (e.g. camera, traffic light), and b) the server (RTA Application server, SP Infr Application Server) that is hosted in a cloud. When mobile networks are used, the interfaces that both parts use to exchange data (e.g. sensor information of road infrastructure to an RTA Server) and/or provide data to the ToD sub-system (e.g. camera data of the infrastructure to ToD AS) are similar to the interfaces presented in Section 8.1.

Figure 30 shows the interfaces of an infrastructure device and an infrastructure server within the 5GS, including both user plane and control plane interfaces:

- Interfaces between the Application Server (RTA or SP Infr) and the communication network:
    - N33/NNFnef: Reference point between NEF and an Application Function (AF). This interface allows the RTA server or SP Infr application server to request and receive information e.g. analytics, QoS prediction that the network provides. The NEF provides access to various services of the network. For instance, Nnef_AnalyticsExposure provides support for network analytics, i.e. Nnef_AFsessionWithQoS requests the network to provide a specific QoS for an AS session, etc. It should be clarified that the RTA server or SP Infr application server and the ToD AS may have different requirements for QoS prediction information (QoS sustainability analytics).
    - N6: Interface between the UPF and a public data network for traffic forwarding.
- Interfaces between the SP or Road Infrastructure and the communication network:
    - Uu: Radio interface between the SP or Road Infrastructure and the radio access network to support both user plane traffic (e.g. infrastructure data packets, application layer control singalling) and control plane traffic (i.e. network signalling packets).

- N1: Reference point between the UE and the AMF for control plane signalling between the vehicle (User Equipment/Communication Component) and the 5GS e.g., for measurements reporting, session management etc

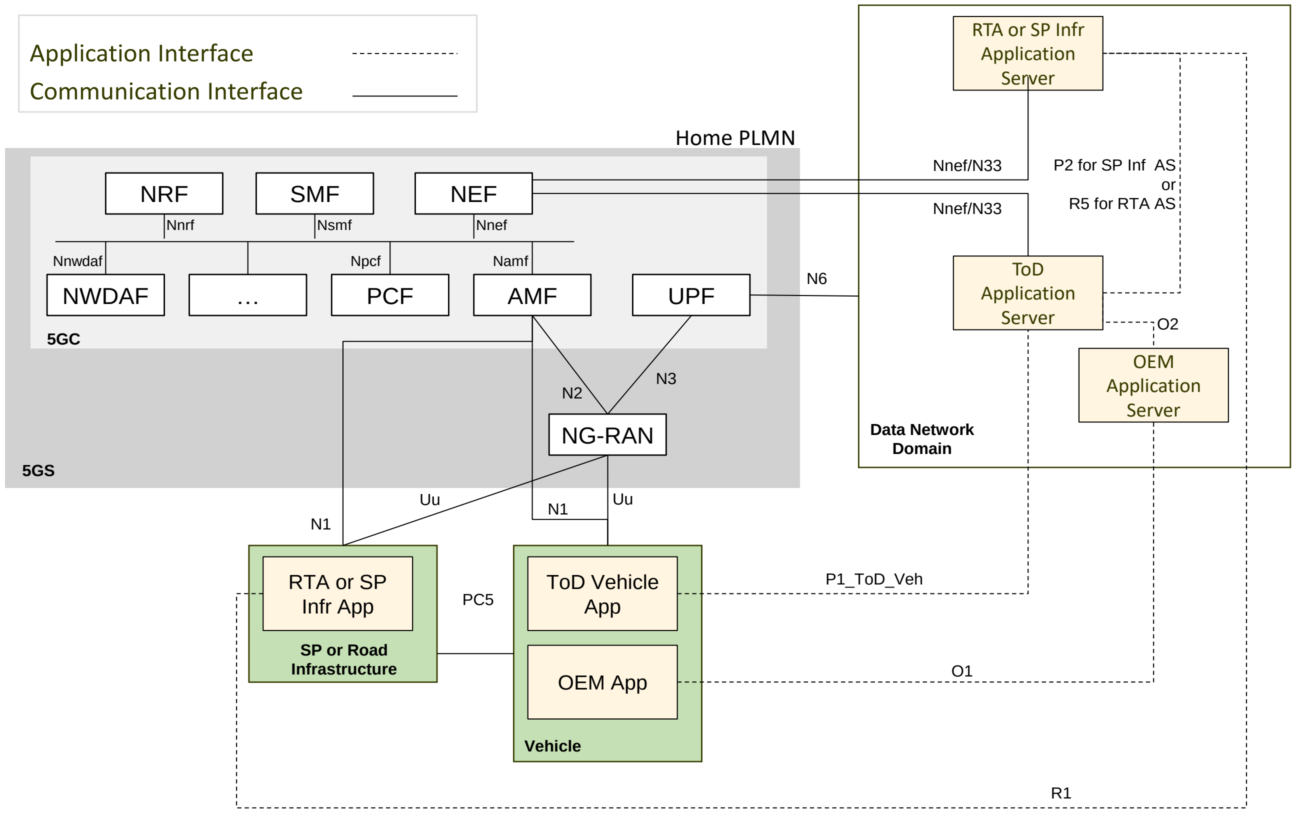


Figure 30: 5G System Architecture (non-roaming case and Infrastructure-based ToD)

9 Conclusion

This technical report from Task 2 of 5GAA ToD cross-working group work item studies technical requirements, enabler technologies, and architectures of systems providing ToD services and use cases studied in Task 1 [2].

This study envisages a progressive three-stage deployment roadmap of ToD services in different operational and market environments, namely ToD in confined areas, ToD in dedicated local public roads or areas, and ToD for cross-region mobility. The study on the application layer architecture of ToD systems in different stages shows:

- In the first stage, i.e. ToD services in confined areas, all components of the ToD system are under the control of the premises owner. Therefore, proprietary protocols can be used for the interfaces among sub-systems and components of such systems. A dedicated private network or public mobile network from a single MNO can be used as the communication solution.
- In the second stage, i.e. ToD services in dedicated local public areas or roads, cross-OEM and cross-SP, interoperability becomes important for market deployment of many services. Therefore, the interface between ToD AS and OEM AS, as well as the interface between ToD AS and ToD Vehicle App from different Service Providers and automotive OEMs need to be standardised or agreed among the stakeholders. In this case, the Interchange Function plays an important role in announcing and discovering ToD services. In this stage, communications in dedicated local areas rely on the mobile network from a single or multiple MNOs.

- In the third stage, i.e. ToD services for cross-region mobility, challenges of cross-OEM, cross-SP, and cross-RTA interoperability raise the need for standardisation or agreement on the interfaces among RTA AS, ToD AS, and OEM AS across different regions and stakeholders, in addition to the interface between ToD AS and ToD Vehicle App of different ToD Service Providers and automotive OEMs. Interchange Functions, which can be implemented by either commercial Service Providers or authorities, facilitate service discovery and scalable information exchange in the backend of stakeholders in different regions. Public mobile networks from multiple MNOs are required for communication solutions to ensure service availability in cross-region areas.

For ToD service provisioning, readiness of application and features inside the vehicle must show a maturity level that fulfils technical requirements for automated driving, according to the SAE Levels 3, 4 and 5. This includes between others, on-board sensors, communication, and actuator components. This Technical Report refers to vehicle technology (with no claim of completeness) enabling different types of ToD services in the future. Details on C-V2X sidelink, HD digital maps, precise positioning, LiDAR, RADAR, video cameras and ultrasonic capabilities are provided, and their roles with respect to different types of ToD are discussed.

The ToD operator sub-system is a key component of the ToD system and may involve very advanced technologies to improve the remote operation of vehicles, including human sensors to gather information from ToD operators to keep track of their real-time state, human actuators to provide tactile feedback, wheel and pedal sensors/actuators, and advanced high-resolution displays, including augmented reality technology such as immersive glasses. The end-to-end ToD system efficiency relies on well-organised and user-friendly cockpit components that must provide sensors with low measurement latencies, actuators with low delay to mechanical or electrical devices, and extremely low latency video capabilities (all offering maximum reliability).

The infrastructure sub-system can provide improvements in sensor range, and therefore increase safety when performing the ToD operation. In all forms of ToD, reliable two-way network communication between operator and vehicle is necessary. In addition, infrastructure-supported ToD requires seamless and reliable fixed sensor coverage along the road and considerable edge compute capabilities to generate a digital twin of the environment and, in some cases, automatically perform the ToD operation. Therefore, it is likely to be deployed within well-defined environments such factory sites, harbours, airports, etc. or where a sensor and the edge-infrastructure environment is implemented for a wider range of use cases.

Field tests have proven performance capabilities of 4G and 5G networks supporting ToD services for both Indirect Control ToD and Direct Control ToD operations. Although advanced cellular network features such as QoS provisioning, Predictive QoS, and network reselection improvement for inter-PLMN handover are not mandatory for ToD systems from the functional safety perspective, according to the black-channel approach, these features are important for ensuring service availability and user experiences in market deployment of ToD services. Communication security for ToD services can be ensured using state-of-the-art security solutions for session-based communication applications, such as TLS with PKI-based authentication mechanism.

Communication network architectures for ToD services presented in this study, using single MNO or multiple MNO networks and considering the support of the infrastructure sub-system in the ToD operation. These architectures are applicable to different market deployment stages of the ToD services and will address the performance and functional communication requirements of the ToD services. Examples of the required interfaces between the communication architecture and the ToD system application layer architecture have also been presented.

To facilitate market deployment of ToD services, especially for Stage 2 and 3 in the ToD service roadmap, this study recommends that relevant MNOs, road operators and authorities and other stakeholders work jointly on proper cellular network coverage for the relevant road environments and on improving network reselection performance, as suggested in [27] and [20]. Furthermore, the foreseeable increase in spectrum demands for V2N communication driven by ToD services in public areas deserves the attention of spectrum regulators mindful of supporting innovative transport and mobility services.

Annex A: Service level requirements of Infrastructure-based Tele-Operated Driving

The following table from the 5GAA WG1 white paper C-V2X Use Case Volume II [5] shows the service level performance requirements of Infrastructure-based Tele-Operated Driving.

Table 15: Service level requirements of Infrastructure-based Tele-Operated Driving

Infrastructure-based Tele-operated Driving			
SLR Title	**SLR Unit**	**SLR Value**	**Explanations/Reasoning/Background**
Range	**[m]**	1000 total	*Max driving distance from start of emergency until safe stop.*
Information requested / generated	**Quality of information / Information needs**	From RADAR to local compute unit for sensor fusion 80-160 Kbps From cameras to local compute unit 5 – 8 Mbps per camera (Video Streaming) From LiDAR sensors to local compute unit: 35 Mbps per sensor From Infrastructure to ToD operator: Stream of environmental data after sensor fusion at the edge From ToD operator to HV: Up to 1000	*Assuming RADAR sensors already generate object lists for observed vehicles then the required bandwidth depends on traffic density.* *The number of cameras needed depends on the complexity of the road including number of lanes. Each camera is separately connected to the edge computer. This assumes also H264 compression. Video pre-processing, detection and classification of objects by camera is compute-intensive, therefore connecting more than two cameras to a state-of-the-art server is currently unlikely.* *Assuming each LiDAR sensor create point clouds and not object lists.* *This could happen on the same compute node. Therefore this speed requirement will be handled by local buses like Peripheral Component Interconnect Express (PCIe). Pre-processed environment model data, e.g. in form of object lists that contain among others vehicle types, sizes, speed and direction requires only limited bandwidth, depending on the number of objects in the environment model this is estimated between 50-500 kbps.*

		bytes per message (up to 400 Kbps) (Commands from ToD operator)	From ToD operator to HV: *A machine-based ToD operator will most likely transmit trajectories instead of direct actuation commands. The size of command messages, e.g. a) turn steering wheel, direction, angle and b) apply the brake, brake pressure, etc. including appropriate security headers. The command messages will be sent every 20 ms (maximum 50 messages per second).*
Service level latency	**[ms]**	From infrastructure to ToD operator: 50 From ToD operator to HV: 50	Round-trip time = 100 ms From ToD operator to HV*: Depends on the reaction time needed and which is directly related to the maximum driving speed allowed.*
Service level reliability		From sensors to edge compute node: 99% From ToD operator to HV: 99.999% (Very high)	This is comparable to the sensor inside the car. From ToD operator to HV: *The transmission of commands or paths from the ToD operator require a very high level of reliability, since this affects the safe and efficient operation of the AV. In addition, the video streams and/or sensor information that should also be sent with high reliability to make sure that the ToD operator has the correct (current) view of the surroundings.*
Velocity	**[m/s]**	2.78	*<10 km/h is the maximum considered speed that remote steering needs to be provided due to a situation of high uncertainty.*
Vehicle Density	**[vehicle/km^2]**	1200 vehicles/km2 at 20 km/h A maximum or around 10 vehicles, i.e. 0.05% of the total density, have the service provided to them.	*Around 200 vehicles will fit on a 1 km highway strip with three lanes in each direction.* *Assumptions:* • *Lane width of 3 m (for the two directions around 20 m).* • *Inter-vehicles distance required in traffic jam (maximum speed 20 km/h):11 m.* • *Average vehicle length of 4.5 m.* • *Three highway crossings (bridges).* *Vehicle density reflects the number of HVs. Many more RVs could be present.*

Positioning accuracy	**[m]**	0.1 (3σ)	*Positioning accuracy is needed to navigate around objects blocking parts of the driving land and to navigate through small gaps between two or more objects.*
Interoperability / Regulatory / Standardisation Required	**[yes/no]**	Yes/Yes/Yes	*Interoperability and standardisation is needed between the infrastructure (e.g. camera) and the ToD server. It is possible, however, that the edge servers are set up as a multi-tenant system where each car OEM runs its own system.* *Regulation is needed because authorities may need to specify maximum speed, minimum accuracy, data formats, etc.*

Annex B: Standardised 5QI to QoS characteristics mapping

The mapping between 5QI to QoS characteristics in the 5G System are defined in 3GPP TS 23.501 [14], as shown in Table 16.

Table 16. Standardised 5QI to QoS characteristics mapping [14]

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget (NOTE 3)	Packet Error Rate	Default Maximum Data Burst Volume (NOTE 2)	Default Averaging Window	Example Services
1	GBR (NOTE 1)	20	100 ms (NOTE 11, NOTE 13)	10^{-2}	N/A	2000 ms	Conversational Voice
2		40	150 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Conversational Video (Live Streaming)
3		30	50 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Real Time Gaming, V2X messages (see TS 23.287). Electricity distribution – medium voltage, Process automation monitoring
4		50	300 ms (NOTE 11, NOTE 13)	10^{-6}	N/A	2000 ms	Non-Conversational Video (Buffered Streaming)
65 (NOTE 9, NOTE 12)		7	75 ms (NOTE 7, NOTE 8)	10^{-2}	N/A	2000 ms	Mission Critical user plane Push To Talk voice (e.g. MCPTT)
66 (NOTE 12)		20	100 ms (NOTE 10, NOTE 13)	10^{-2}	N/A	2000 ms	Non-Mission-Critical user plane Push To Talk voice
67 (NOTE 12)		15	100 ms (NOTE 10, NOTE 13)	10^{-3}	N/A	2000 ms	Mission Critical Video user plane
75 (NOTE 14)							
71		56	150 ms (NOTE 11, NOTE 13, NOTE 15)	10^{-6}	N/A	2000 ms	'Live' Uplink Streaming (e.g. TS 26.238)
72		56	300 ms (NOTE 11, NOTE 13, NOTE 15)	10^{-4}	N/A	2000 ms	'Live' Uplink Streaming (e.g. TS 26.238)
73		56	300 ms (NOTE 11, NOTE 13, NOTE 15)	10^{-8}	N/A	2000 ms	'Live' Uplink Streaming (e.g. TS 26.238)
74		56	500 ms (NOTE 11, NOTE 15)	10^{-8}	N/A	2000 ms	'Live' Uplink Streaming (e.g. TS 26.238)
76		56	500 ms (NOTE 11, NOTE 13, NOTE 15)	10^{-4}	N/A	2000 ms	'Live' Uplink Streaming (e.g. TS 26.238)
5	Non-GBR (NOTE 1)	10	100 ms NOTE 10, NOTE 13)	10^{-6}	N/A	N/A	IMS Signalling
6		60	300 ms (NOTE 10, NOTE 13)	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g. www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		70	100 ms (NOTE 10, NOTE 13)	10^{-3}	N/A	N/A	Voice, Video (Live Streaming) Interactive Gaming

8		80	300 ms (NOTE 13)	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g. www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9		90					
69 (NOTE 9, NOTE 12)		5	60 ms (NOTE 7, NOTE 8)	10^{-6}	N/A	N/A	Mission Critical delay sensitive signalling (e.g. MC-PTT signalling)
70 (NOTE 12)		55	200 ms (NOTE 7, NOTE 10)	10^{-6}	N/A	N/A	Mission Critical Data (e.g. sample services are the same as 5QI 6/8/9)
79		65	50 ms (NOTE 10, NOTE 13)	10^{-2}	N/A	N/A	V2X messages (see TS 23.287)
80		68	10 ms (NOTE 5, NOTE 10)	10^{-6}	N/A	N/A	Low Latency eMBB applications Augmented Reality
10		90	832ms (NOTE 13) (NOTE 17)	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g. www, e-mail, chat, ftp, p2p file-sharing, progressive video, etc.) and any service that can be used over satellite access type with these characteristics
82	Delay-critical GBR	19	10 ms (NOTE 4)	10^{-4}	255 bytes	2000 ms	Discrete Automation (see TS 22.261)
83		22	10 ms (NOTE 4)	10^{-4}	1354 bytes (NOTE 3)	2000 ms	Discrete Automation (see TS 22.261); V2X messages (UE - RSU Platooning, Advanced Driving: Cooperative Lane Change with low LoA. See TS 22.186, TS 23.287)
84		24	30 ms (NOTE 6)	10^{-5}	1354 bytes (NOTE 3)	2000 ms	Intelligent Transport Systems (see TS 22.261)
85		21	5 ms (NOTE 5)	10^{-5}	255 bytes	2000 ms	Electricity Distribution- high voltage (see TS 22.261). V2X messages (Remote Driving. See TS 22.186, NOTE 16, see TS 23.287)
86		18	5 ms (NOTE 5)	10^{-4}	1354 bytes	2000 ms	V2X messages (Advanced Driving: Collision Avoidance, Platooning with high LoA. See TS 22.186, TS 23.287)
87		25	5 ms (NOTE 4)	10^{-3}	500 bytes	2000 ms	Interactive Service - Motion tracking data, (see TS 22.261)

88		25	10 ms (NOTE 4)	10^{-3}	1125 bytes	2000 ms	Interactive Service - Motion tracking data, (see TS 22.261)
89		25	15 ms (NOTE 4)	10^{-4}	17000 bytes	2000 ms	Visual content for cloud/edge/split rendering (see TS 22.261)
90		25	20 ms (NOTE 4)	10^{-4}	63000 bytes	2000 ms	Visual content for cloud/edge/split rendering (see TS 22.261)

NOTE 1: A packet which is delayed more than PDB is not counted as lost, thus not included in the PER.

NOTE 2: It is required that default MDBV is supported by a PLMN supporting the related 5QIs.

NOTE 3: The Maximum Transfer Unit (MTU) sise considerations in clause 9.3 and Annex C of TS 23.060 are also applicable. IP fragmentation may have impacts to CN PDB, and details are provided in clause 5.6.10 of [14].

NOTE 4: A static value for the CN PDB of 1 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN PDB is used, see clause 5.7.3.4 of [14].

NOTE 5: A static value for the CN PDB of 2 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN PDB is used, see clause 5.7.3.4 of [14].

NOTE 6: A static value for the CN PDB of 5 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN PDB is used, see clause 5.7.3.4 of [14].

NOTE 7: For Mission Critical services, it may be assumed that the UPF terminating N6 is located 'close' to the 5G_AN (roughly 10 ms) and is not normally used in a long distance, home routed roaming situation. Hence a static value for the CN PDB of 10 ms for the delay between a UPF terminating N6 and a 5G_AN should be subtracted from this PDB to derive the packet delay budget that applies to the radio interface.

NOTE 8: In both RRC Idle and RRC Connected mode, the PDB requirement for these 5QIs can be relaxed (but not to a value greater than 320 ms) for the first packet(s) in a downlink data or signalling burst in order to permit reasonable battery saving (DRX) techniques.

NOTE 9: It is expected that 5QI-65 and 5QI-69 are used together to provide Mission Critical Push to Talk service (e.g. 5QI-5 is not used for signalling). It is expected that the amount of traffic per UE will be similar or less compared to the IMS signalling.

NOTE 10: In both RRC Idle and RRC Connected mode, the PDB requirement for these 5QIs can be relaxed for the first packet(s) in a downlink data or signalling burst in order to permit battery saving (DRX) techniques.

NOTE 11: In RRC Idle mode, the PDB requirement for these 5QIs can be relaxed for the first packet(s) in a downlink data or signalling burst in order to permit battery saving (DRX) techniques.

NOTE 12: This 5QI value can only be assigned upon request from the network side. The UE and any application running on the UE is not allowed to request this 5QI value.

NOTE 13: A static value for the CN PDB of 20 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface.

NOTE 14: This 5QI is not supported in this Release of the specification as it is only used for transmission of V2X messages over MBMS bearers as defined in TS 23.285 but the value is reserved for future use.

NOTE 15: For 'live' uplink streaming (see TS 26.238), guidelines for PDB values of the different 5QIs correspond to the latency configurations defined in TR 26.939. In order to support higher latency reliable streaming services (above 500 ms PDB), if different PDB and PER combinations are needed these configurations will have to use non-standardised 5QIs.

NOTE 16: These services are expected to need much larger MDBV values to be signalled to the RAN. Support for such larger MDBV values with low latency and high reliability is likely to require a suitable RAN configuration, for which, the simulation scenarios in TR 38.824 may contain some guidance.

NOTE 17: The worst case one way propagation delay for GEO satellite is expected to be ~270 ms, ,~ 21 ms for LEO at 1200 km, and 13 ms for LEO at 600 km. The UL scheduling delay that needs to be added is also typically 1 RTD e.g. ~540 ms for GEO, ~42 ms for LEO at 1200 km, and ~26 ms for LEO at 600 km. Based on that, the 5G-AN Packet delay budget is not applicable for 5QIs that require 5G-AN PDB lower than the sum of these values when the specific types of satellite access are used (see TS 38.300). 5QI-<New Value> can accommodate the worst case PDB for GEO satellite type.